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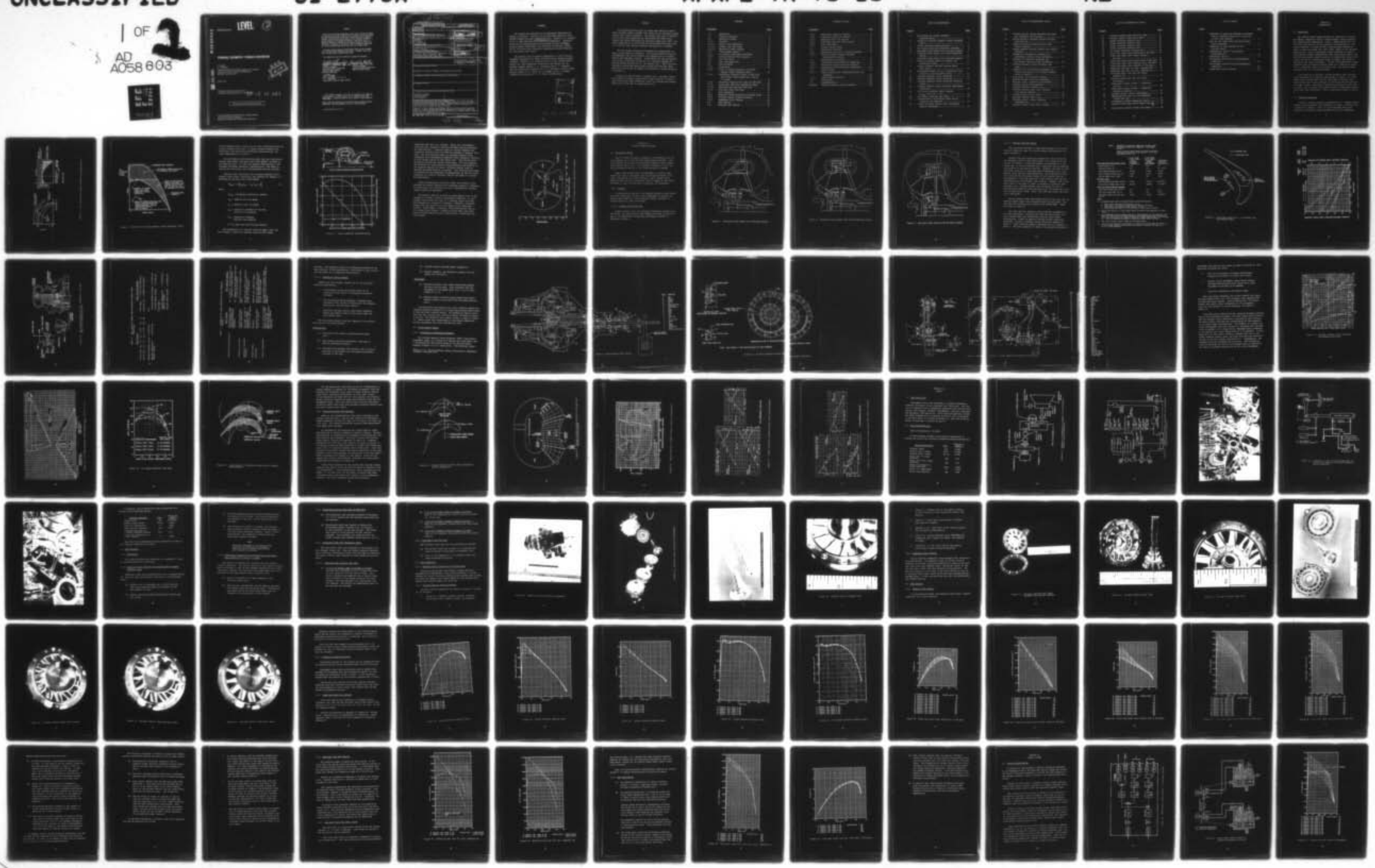

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VARIABLE GEOMETRY TORQUE CONVERTER

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AiRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA 85034

APRIL 1978

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This report documents the work performed under Air Force Systems Command Contract F33615-76-C-2013. Program objective was to design and evaluate a breadboard variable reactor system using the B-1 secondary power system torque converter.

Results of the evaluation indicate that a variable reactor can be used in a small, high-speed torque converter to control input and output power schedules, during an acceleration between speed ratios from zero to approximately 0.9.

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FOREWORD

This report was prepared by the AiResearch Manufacturing Company of Arizona. The work was accomplished under Air Force Systems Command Contract F33615-76-C-2013. Messrs. W. F. Koepsel and K. W. Benn directed the program for AiResearch. Technical direction and administration was provided by Buryl McFadden, Captain Herbert Schumacher, and Lieutenant David Hall (AFAPL/POP-1), Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

The authors wish to express appreciation to the following AiResearch personnel for their contributions to program accomplishment: Messrs. G. L. Perrone and H. T. Liu, fluid dynamics design; Mr. John Haugeland, stress work and design; Mr. R. Roetman, design; Messrs. J. A. Carpenter and D. P. Thomason, test and fabrication liaison; Mr. H. T. Hattasch, control system design; Messrs. W. W. Nehls, E. E. Graham, and M. L. Vaughn, assembly and testing; Mr. A. T. Koen, documentation.

SUMMARY

The program objective was to design and evaluate a breadboard variable reactor system (VRS) using the B-1 secondary power system (SPS) torque converter. The primary goal was to optimize main engine start capability by controlling the power match between the torque converter and auxiliary power unit (APU); the power match was to be controlled by varying absorbed power from 30 to 120 hp, and reducing flowpath disruption to a minimum.

The B-1 torque converter performance was established on a test rig and used as a baseline. The torque converter then was disassembled, and static reactor was replaced with a variable reactor and necessary linkage. Performance data was accumulated with reactor vane angle varied at 2.5° intervals between the maximum closed setting (27.5°) and nominal (0°). Data also were obtained at positions open beyond nominal and with the vanes modulated from closed to nominal and nominal to closed during an acceleration.

Results of the evaluation indicate that a variable reactor can be used in a small, high-speed torque converter to control input and output power schedules, during an acceleration between speed ratios from zero to approximately 0.9.

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SECTION I
INTRODUCTION

1.1 Background

Gas turbine output power varies as a function of altitude and ambient temperature while a fixed geometry torque converter has constant power absorption. Figure 1 shows typical gas turbine and fixed geometry torque converter characteristics. The torque converter is sized to have a maximum power absorption equal to auxiliary power unit (APU) power output at the selected design point. When a nonvariable torque converter is used at altitudes and ambient temperatures lower than design values, the APU will have excess power available; at higher than design altitudes, the APU has insufficient power available, and would be stalled by the torque converter. Further, the nonvariable torque converter does not absorb constant power as a function of speed ratio. Therefore, even at the design point, the APU has power available that is not being utilized.

The incentive to provide a torque converter with variable power absorption, at constant input speed, is clear. In a secondary power system (SPS) such as that used in the B-1, this would enable the torque converter to absorb and utilize the full APU power output, resulting in improved utilization of APU capabilities, such as faster main engine starts or concurrent secondary power load absorption. This is graphically shown in Figure 2.

1.2 General Discussion

The basic torque converter configuration is a simple, three-element type consisting of an impeller (or pump), a turbine, and a reactor (or stator). This is a fluid-dynamic device and operates by exchanging energy between the various components

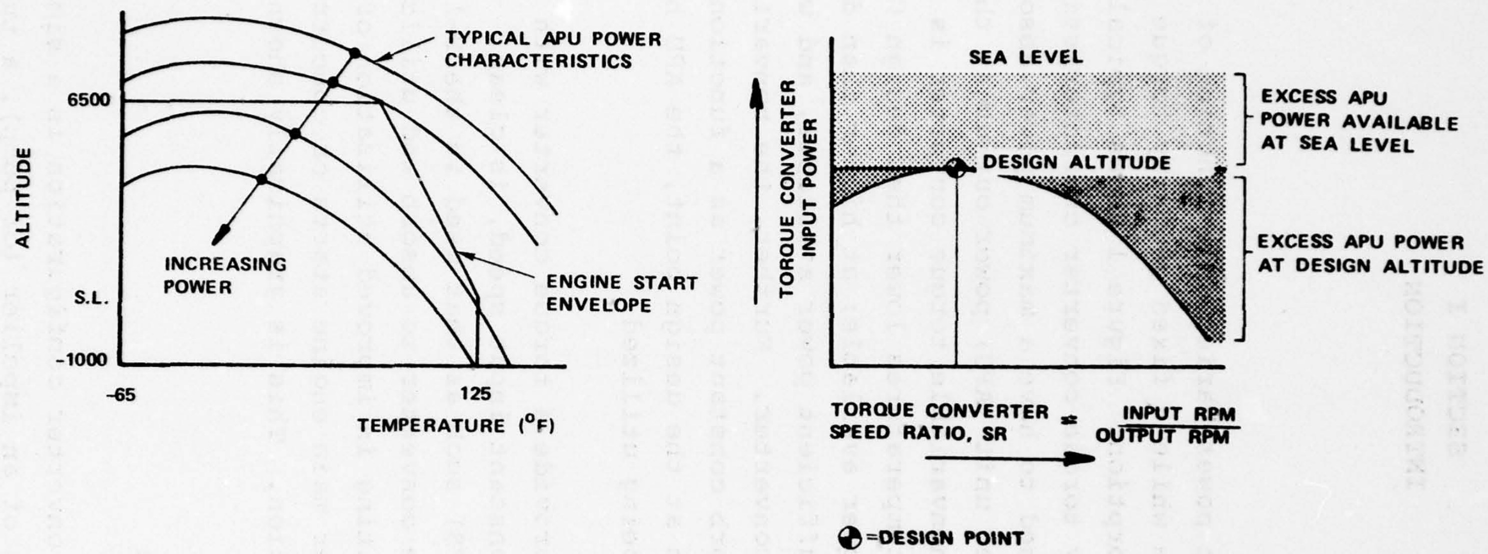


Figure 1. Gas turbine and torque converter characteristics.

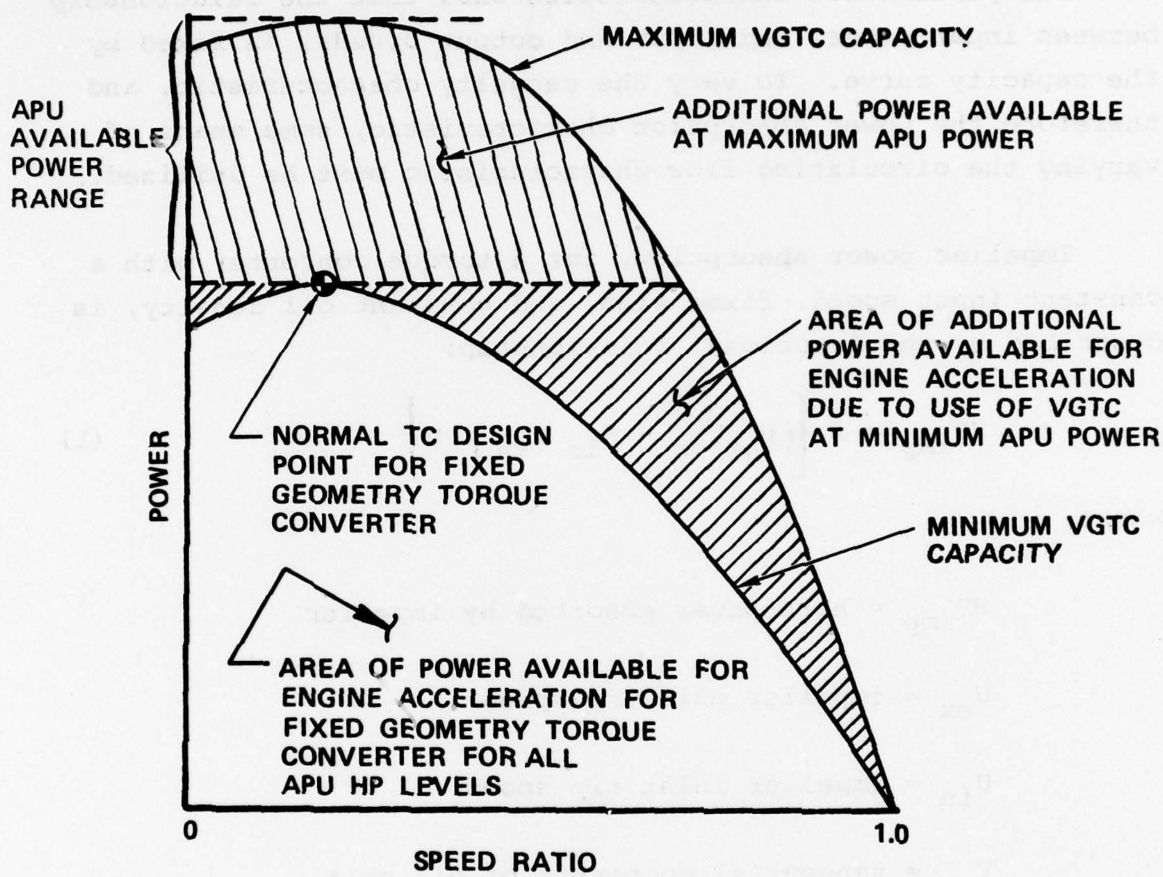


Figure 2. Payoff for variable geometry torque converter (VGTC).

and the working fluid, usually an oil that circulates around the torque converter flow path. A typical torque converter configuration, and associated performance characteristics, are shown schematically in Figure 3.

The performance characteristics show that the relationship between input power, and input and output speeds, is fixed by the capacity curve. To vary the capacity characteristic, and therefore the power absorption characteristic, some means of varying the circulating flow characteristic must be utilized.

Impeller power absorption, for a torque converter with a constant input speed, fixed size, and constant oil density, is described by the functional relationship:

$$HP_{imp} = f\left[\left(U_{ex}V_{ex} - U_{in}\ V_{in}\right) M\right] \qquad (1)$$

where,

HP_{imp} = horsepower absorbed by impeller

U_{ex} = impeller exit tip speed

U_{in} = impeller inlet tip speed

V_{ex} = tangential component of oil exit velocity from impeller

V_{in} = tangential component velocity from impeller

M = oil mass flow rate through impeller

The prerequisites of constant impeller speed, size, and fluid density, imply that impeller inlet and exit blade

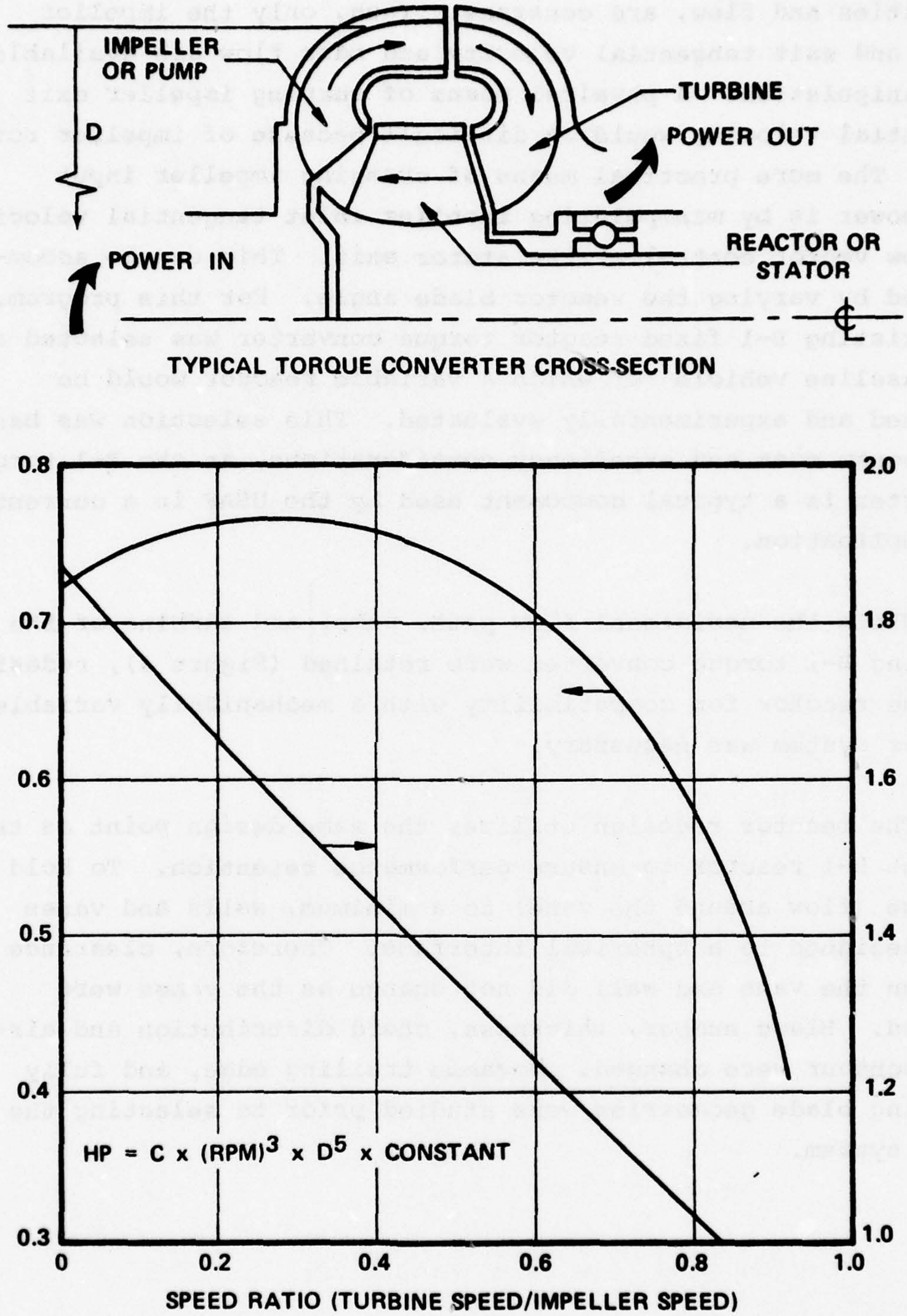


Figure 3. Torque converter characteristics.

velocities and flow, are constant. Thus, only the impeller inlet and exit tangential velocity and mass flow are available for manipulation. A physical means of varying impeller exit tangential velocity would be difficult because of impeller rotation. The more practical means of changing impeller input horsepower is by manipulating impeller inlet tangential velocity, by flow vector control at the stator exit. This can be accomplished by varying the reactor blade angle. For this program, the existing B-1 fixed reactor torque converter was selected as the baseline vehicle for which a variable reactor would be designed and experimentally evaluated. This selection was based on program cost and expediency considerations, as the B-1 torque converter is a typical component used by the USAF in a current SPS application.

While the meridional flow path, pump, and turbine of the existing B-1 torque converter were retained (Figure 4), redesigning the reactor for compatibility with a mechanically variable reactor system was necessary.

The reactor redesign utilizes the same design point as the current B-1 reactor to ensure performance retention. To hold leakage (flow around the vane) to a minimum, walls and vanes were designed to a spherical interface. Therefore, clearance between the vane and wall did not change as the vanes were rotated. Blade number, thickness, chord distribution and airfoil contour were changed. Movable trailing edge, and fully rotating blade geometries were studied prior to selecting the final system.

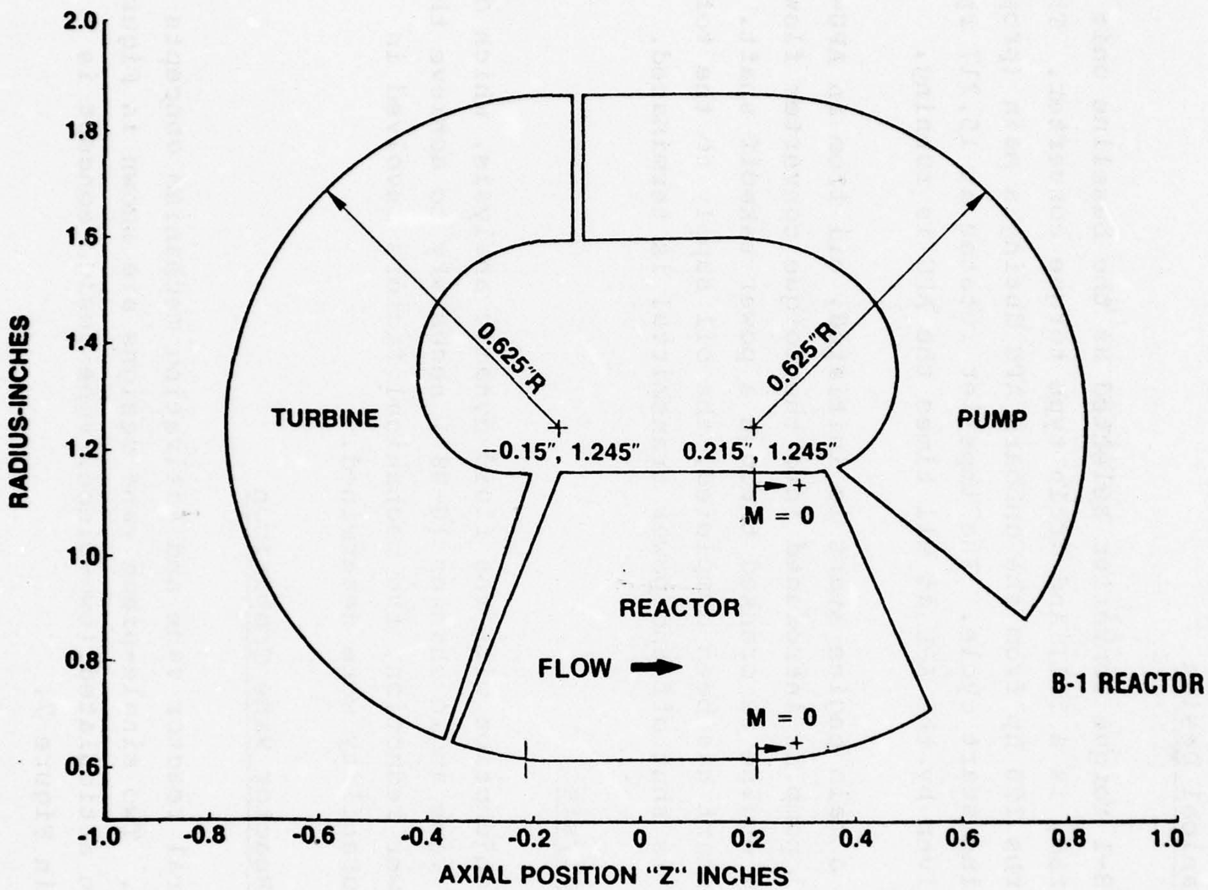


Figure 4. B-1 torque converter meriodional flowpath.

SECTION II

VARIABLE REACTOR DESIGN

2.1 Mechanical Design

The B-1 torque converter selected as the baseline unit for this program, is a fill and drain type torque converter. The unit absorbs 120 hp from the onboard APU during a main (propulsion) engine start cycle. The impeller rotates at 15,217 rpm and is driven by the APU at all times the APU is running.

When a main engine start is initiated, oil from an APU-driven oil pump is introduced into the torque converter flowpath. The engine is cranked through a power takeoff shaft. When the start has been completed, the oil supply to the torque converter is shut off and power transmittal is terminated.

2.1.1 Analysis

In conjunction with the fluid dynamic analysis, which determined the vane angle changes (0-28°) necessary to achieve the design power reduction, the mechanical factors involved in reactor durability were determined.

2.1.1.1 Reactor Vane Comparison

Several reactor vane and activating mechanism concepts were evaluated. Two single-piece vane designs are shown in Figures 5 and 6. An articulated (two-piece) vane design concept is depicted in Figure 7.

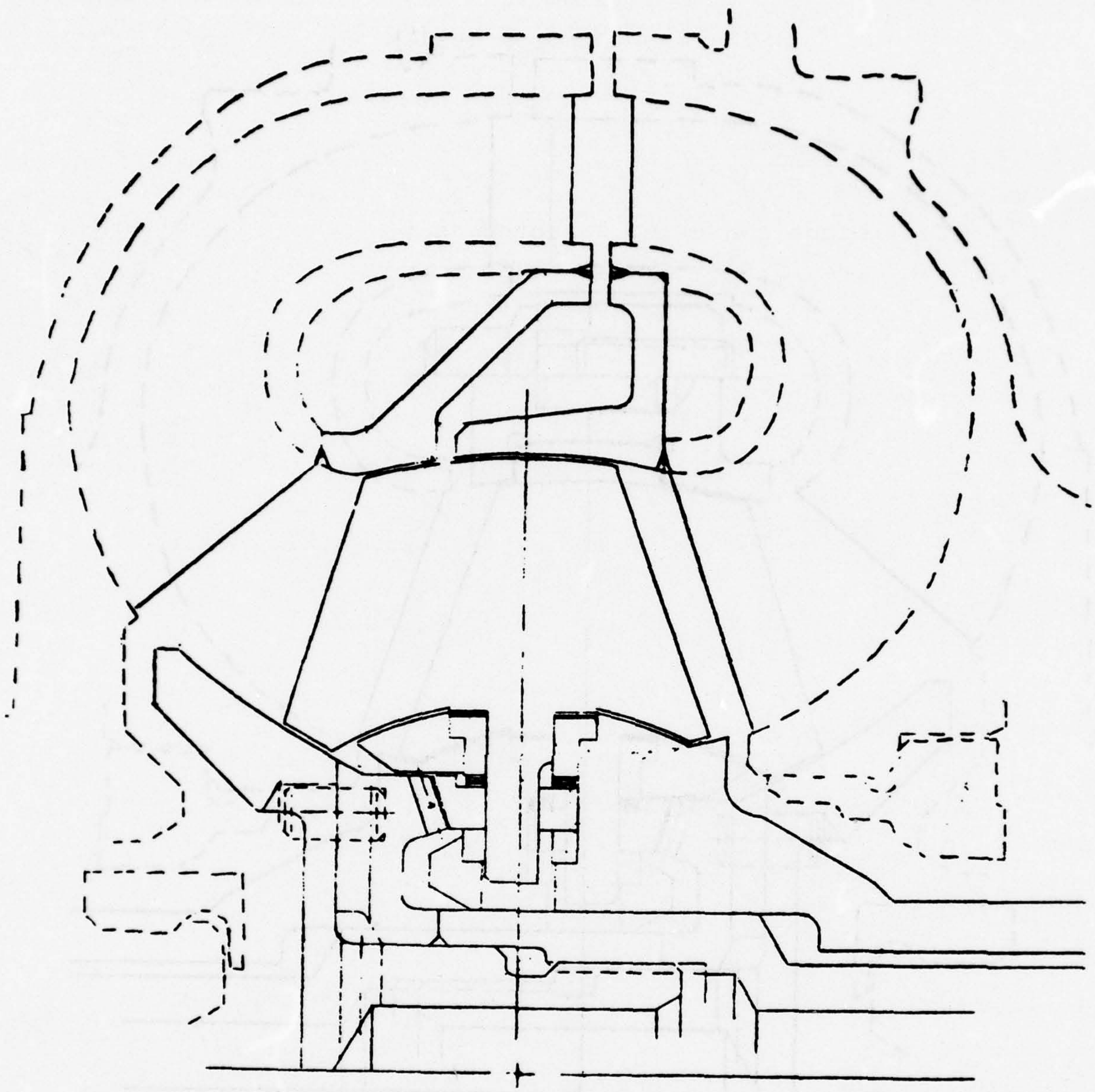


Figure 5. One-piece blade design with two-piece shroud.

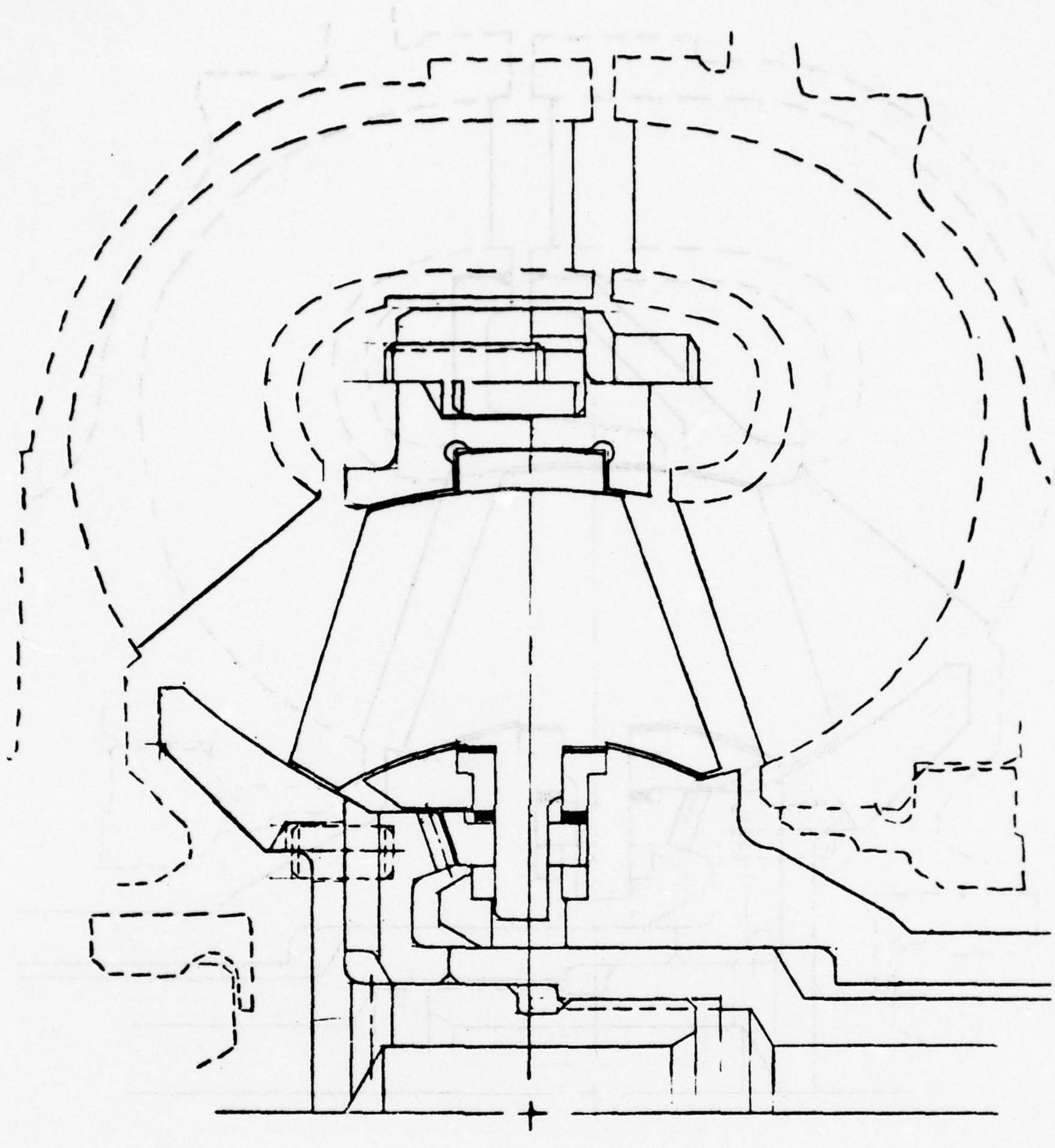


Figure 6. One-piece blade design with stator-supported shroud.

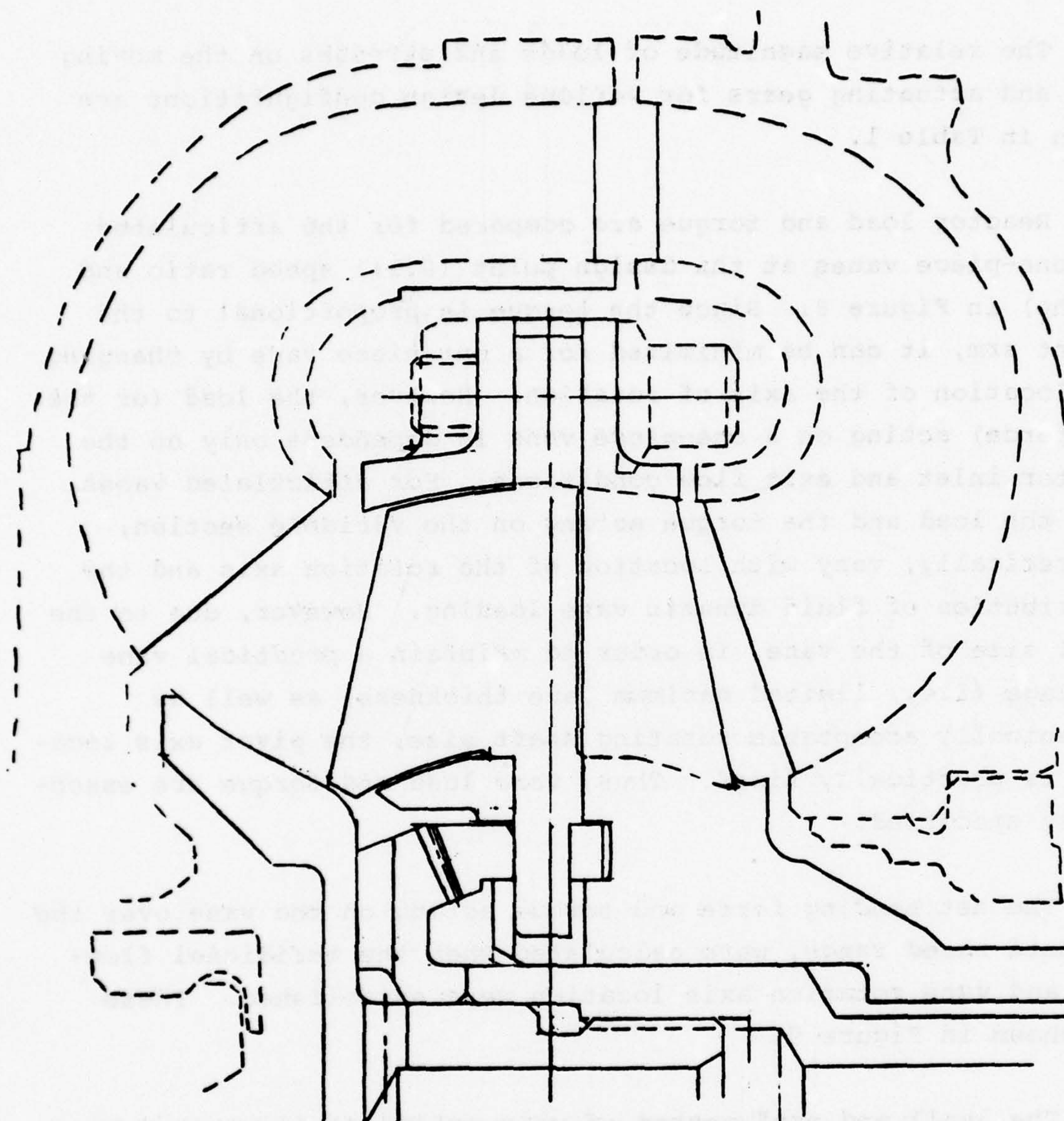


Figure 7. Two-piece blade design with two-piece shroud.

2.1.1.2 Reactor Load and Torque

The relative magnitude of loads and stresses on the moving vane and actuating gears for various design configurations are shown in Table 1.

Reactor load and torque are compared for the articulated and one-piece vanes at the design point (0.1:1 speed ratio and 120 hp) in Figure 8. Since the torque is proportional to the moment arm, it can be minimized for a one-piece vane by changing the location of the axis of rotation. However, the load (or the net force) acting on a one-piece vane is dependent only on the reactor inlet and exit flow conditions. For articulated vanes, both the load and the torque acting on the variable section, theoretically, vary with location of the rotation axis and the distribution of fluid dynamic vane loading. However, due to the small size of the vane, in order to maintain a practical vane blockage (i.e., limited maximum vane thickness) as well as mechanically acceptable rotating shaft size, the pivot axis location is practically fixed. Thus, vane load and torque are essentially specified.

The net bending force and torque acting on the vane over the complete speed range, were calculated when the meridional flowpath and vane rotation axis location were established. These are shown in Figure 9.

The "ball and pin" method of vane actuation (suggested by Air Force Engineers), replacing the ring and pinion gear, was also studied along with preliminary critical parts stress calculations. Figure 10 depicts a design concept using this technique. Critical component stress levels are compared in Table 2. Other important design considerations are compared in Table 3. The most important of these is the angular backlash of

TABLE 1. COMPARISON OF LOADS AND STRESSES ON CRITICAL PARTS OF VARIABLE STATOR FOR 1 PIECE AND 2 PIECE BLADE DESIGNS

Based on Current Torque Converter Design and Loading Configuration Assuming 120 HP Capacity, 15,200 rpm Pump Speed and SR = 0.0

Peak Blade Loads and Stresses (Each)	1 Piece Blade 1/8 In. Single Shank Cantilever Support	2 Piece Blade 1/8 In. Shank Each End Simple Beam Support	Recommended Peak Load or Stress (A)
Torque Load, Lb.-In.	7.40	4.25	7.8
Tangential Force, Lb.	72.5	37.4	38 - 64 (B)
Shaft Bending Stress, Lb/In.^{2}	103,600	12,200	75,000
Shaft Torsional Stress, Lb/ In.^{2}	19,300	11,100	60,000
Bearing Support Load, Lb/In.^{2}	1,930	580	1,000
Peak Gear Tooth			
Bending Stress (Ring Gear) Lb/In.^{2}	21,600	12,420	15,200 (C)
Hertz Stress (Either Gear) Lb/In.^{2}	219,000	125,900	213,000 (C)
Peak Drive Shaft Loads and Stresses			
Peak Clutch Torque Load, Lb.-In.	8.4	4.8	232
Peak Gear Torque Load, Lb.-In.	222	128	232 (D)
Peak Shear Stress from Gear Load Lb/In.^{2}	57,400	33,000	60,000 (D)

NOTES:

(A) Recommended peak loads or stresses based on following materials:

1. Gears = H11 tool steel heat treated to R_C-56.
2. Drive Shaft = H11 brazed to ring gear and treated accordingly.
3. Blade Shaft (including stationary blade) = 17-7PH
4. Moving Blades and Shafts = 17-7PH nitrided or carburized and ground.

(B) First figure applies to 1-piece blade design and second figure applies to 2-piece design.

(C) The recommended flexural stress limits for a given material (in this case H-11 tool steel) can vary over a wide range, depending on the application. Stress levels for bevel gear applications are reduced to allow for nominal misalignment, impact loading, etc. Similar allowances are made for compressive stress limits on gears.

(D) Peak clutch and gear loads on shaft are not simultaneous.

(E) Load and stress values are calculated for a speed ratio of zero when the blades are at the 28° open position (from vertical plane which is normally 120 peak hp on the B-1 torque converter).

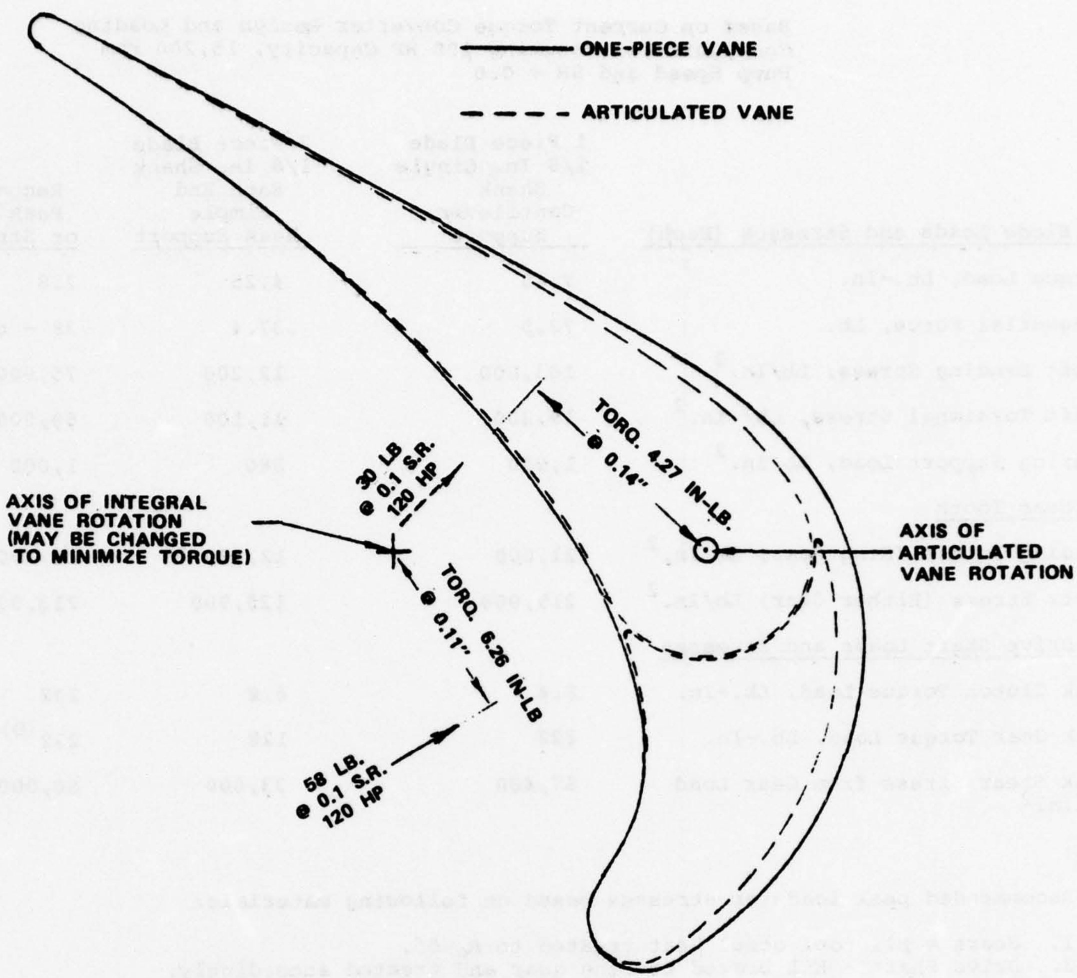


Figure 8. Force and torque acting on integral and articulated vanes.

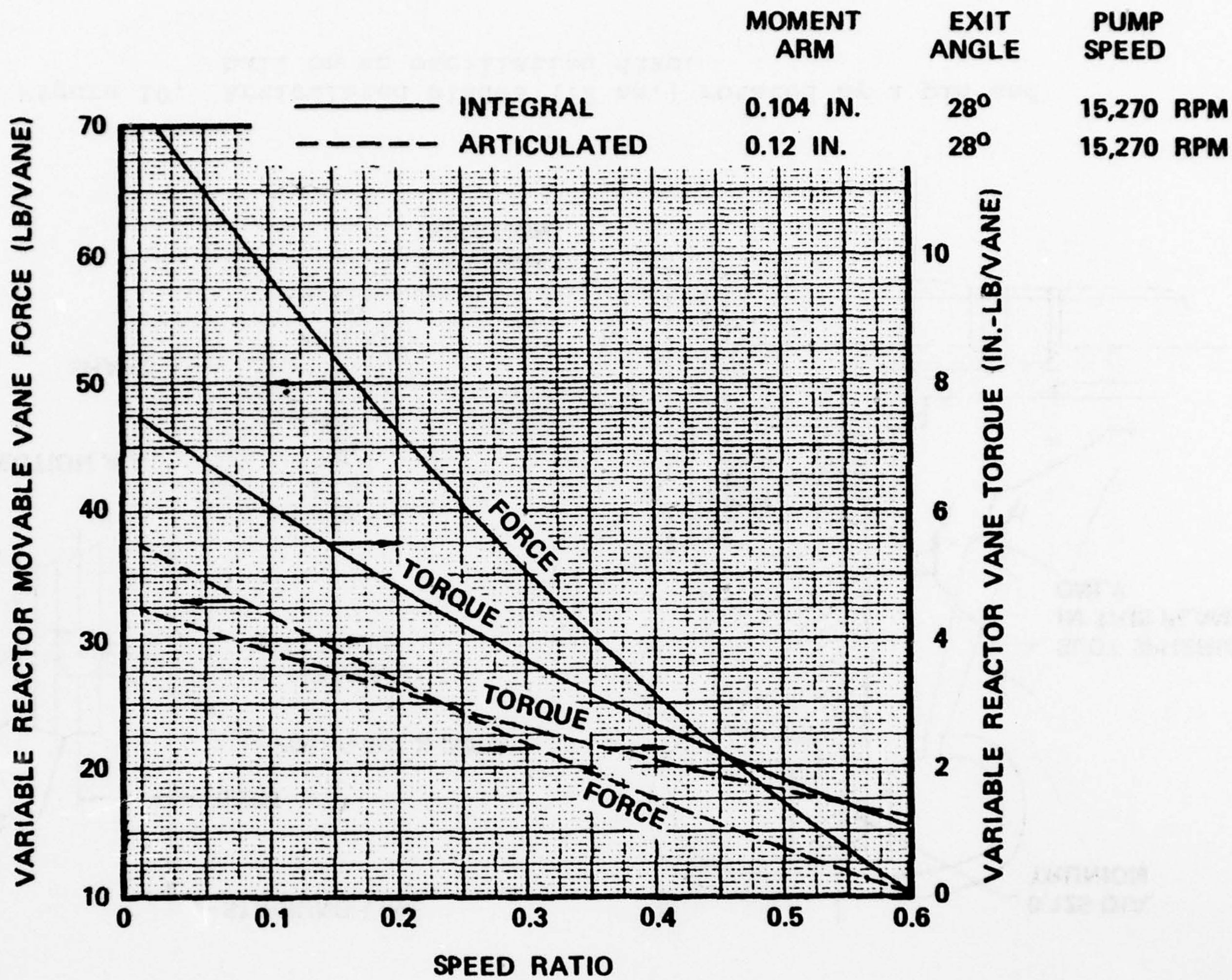


Figure 9. Torque converter variable reactor speed ratio study.

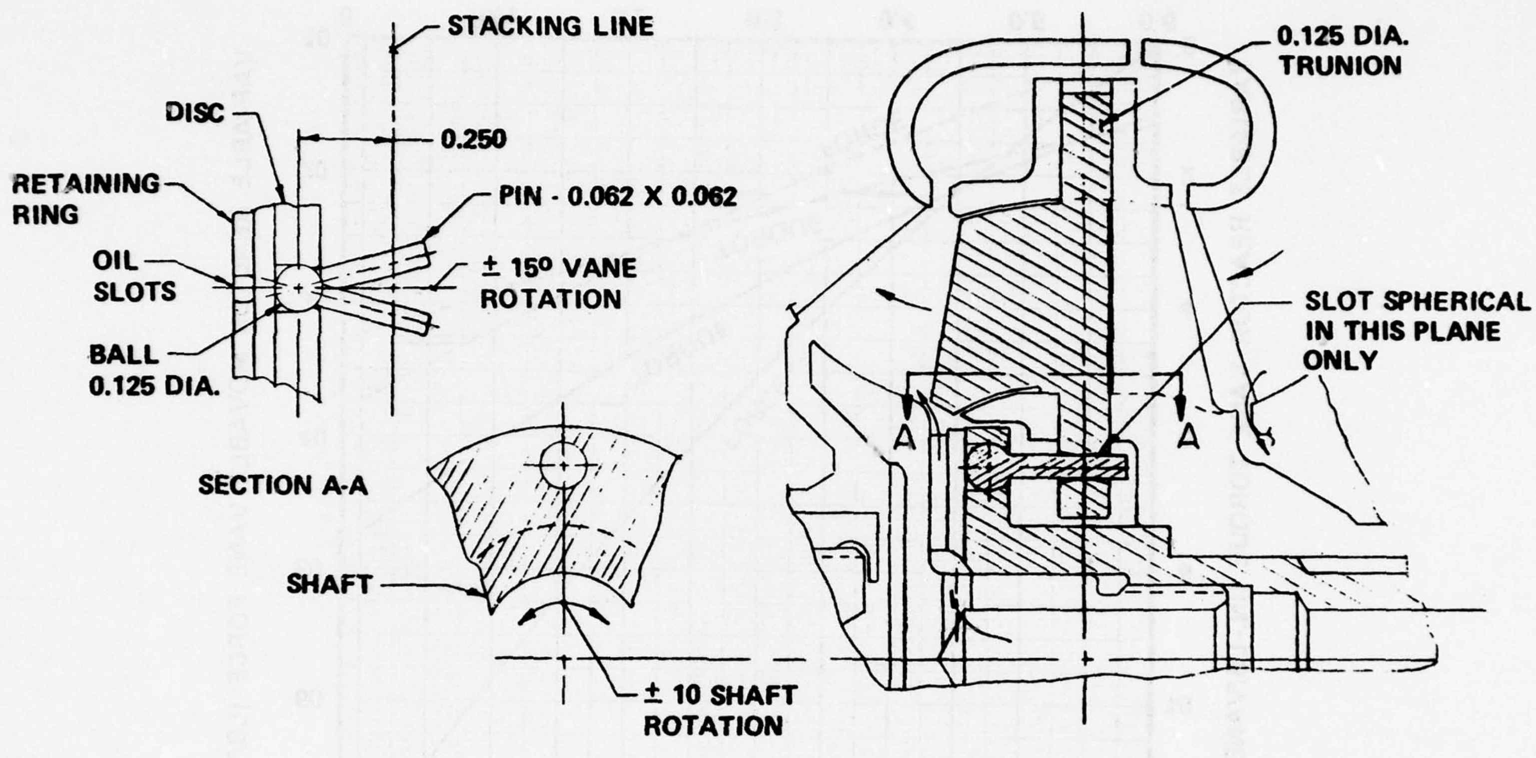


Figure 10. Articulated blades (12 ea.) rotated by a pin and ball on an oscillating disc.

TABLE 2. BALL AND PIN VERSUS GEAR ACTUATION STRESS LEVEL COMPARISON

Gear Design	Ball and Pin Design
Pinion Gear $P_d = 52$ $D_p = 0.461$ $N_p = 24$	Vane Shank = 0.125 inch diameter
Drive Gear $P_d = 52$ $D_p = 1.154$ $N_G = 60$	Actuator Pin = 0.0625 inch square
Maximum Bending Stress = 15,200 psi	Pin:
Maximum Compressive (Hertz) Stress = 154,000 psi	Maximum Bending Stress = 127,800 psi
	Maximum Shear Stress = 12,990 psi
	Vane Shank:
	Maximum Compressive (Hertz) Stress = 179,600 psi
	Maximum Shear Stress = 40,000 psi

TABLE 3. COMPARISON OF GEAR ACTUATOR VS PIN ACTUATOR DESIGN

	Gear Design	Ball and Pin Design
Manufacturing Tolerances	Precision gear forms easily generated on standard production machinery	(a) 0.0555 in. square hole with tilt clearance is quite special (b) Square pin with larger ball end is also quite special
Manufacturing Costs	Standard production shapes lower cost	Special production shapes higher cost
Functional Backlash (Flutter)	For 0.001 - 0.002 in. clearance angular backlash of vane = ± 0.125 to 0.250 degree	For 0.001 to 0.002 in. clearance angular backlash of vane = ± 0.375 to 0.750 degree
Stress Levels	Moderate	Moderate but slightly higher
Materials	Standard tool steel (H-11) for gears	Special M-2 tool steel for ball pins to accommodate potential flutter and high stress
Thrust Compensation	For 5.2 lb-in. torque/blade peak axial gear thrust = 104 lb. Need spring and clutch which also dampens vibration.	No thrust load on actuator shaft. Need spring and clutch for vibration damping.

the vane. The backlash, which is a significant portion of the vane rotation, affects performance, contributes to vane flutter, and can result in an undesired vane position.

2.1.1.3 Mechanical Design Summary

Design and fluid dynamic studies led to the following tentative conclusions:

- o Fluid dynamic loads and torques acting on an articulated vane result in acceptable structural stresses.
- o The articulated design requires a constant vane thickness along the vane rotating axis for assembly, fabrication, and clearance control.
- o One-piece variable reactor vanes cause excessive stress and bearing loads on the control gear and vane support pins.

The articulated reactor vane was compared to a one-piece vane with the following results:

Disadvantages

(a) Restricted vane section stacking/rotating axis point.

(b) More severe flow path disturbance, resulting in greater performance penalty.

(c) Increased flow leakage from pressure side to suction side due to gap between the stationary and movable portions of the vane.

(d) Limited closing (minimum power) capability.

(e) Complex geometry, and therefore, greater risk and higher cost potentials.

Advantages:

(a) Maintains reactor inlet throat area while opening the vane trailing edge. This increases flow and horsepower at low speed ratio (e.g., 0.1:1 as discussed in 2.2.1).

(b) Reduces reactor incidence angle change and corresponding losses as vane opens from the design setting angle.

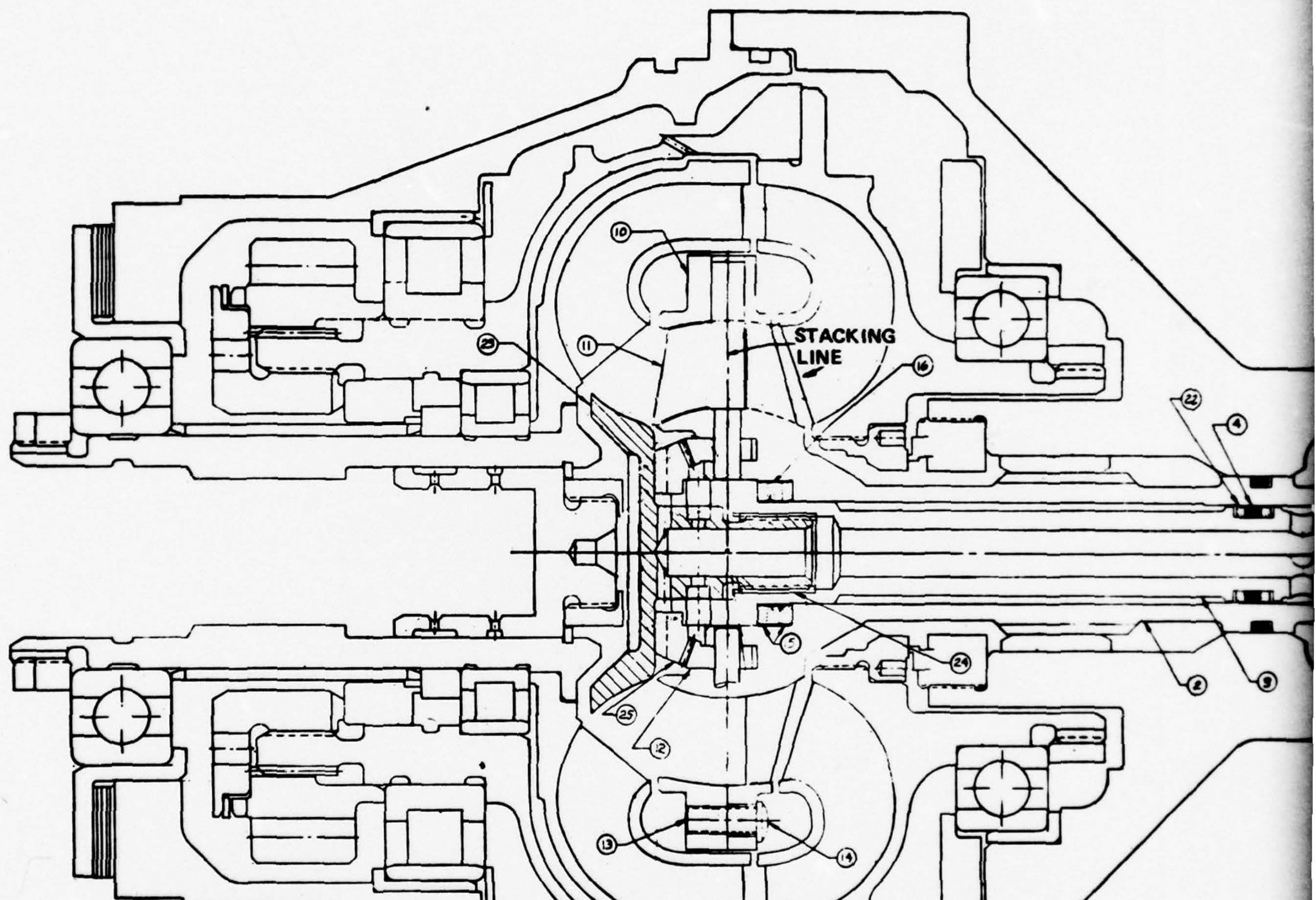
An articulated vane design with a gear actuation system was selected primarily because of the stress and bearing loads caused by the one-piece variable design. The mechanical design layout, with the vane rotation gear actuation system is shown in Figures 11 and 12. The hydraulic vane control system is shown in Figure 13. Twelve vanes were established as the maximum number permitting acceptable gear drive stresses and size.

2.2 Fluid Dynamic Design

2.2.1 Preliminary Performance Estimates

The Variable Reactor Torque Converter (VRTC) input/output horsepower range, as a function of reactor exit vane angle, was a one-dimensional calculation based on the modified Lucas Computer Program* at a 0.1 speed ratio. The predicted output

*Lucas, G. G., Torque Converter Design Calculations, Automobile Engineer, February 1970.



Figure

FIND NO.	NOMENCLATURE
25	GEAR
24	INSERT
23	PLUG, SHAFT
22	RETAINER
21	RETAINER
20	NUT
19	SPRING, HELICAL -COMP.
18	RETAINER, SPRING
17	PIN (SEE FIGURE 12)
16	SHIM
15	BEARING
14	SCREW
13	INSERT
12	GEAR
11	VANES
10	RING - STATOR
9	NUT
8	KEY, NUT LOCKING
7	BEARING
6	NUT
5	PACKING
4	PACKING
3	ACTUATOR SHAFT
2	STATOR
1	TORQUE CONVERTER ASSY.-R.H.

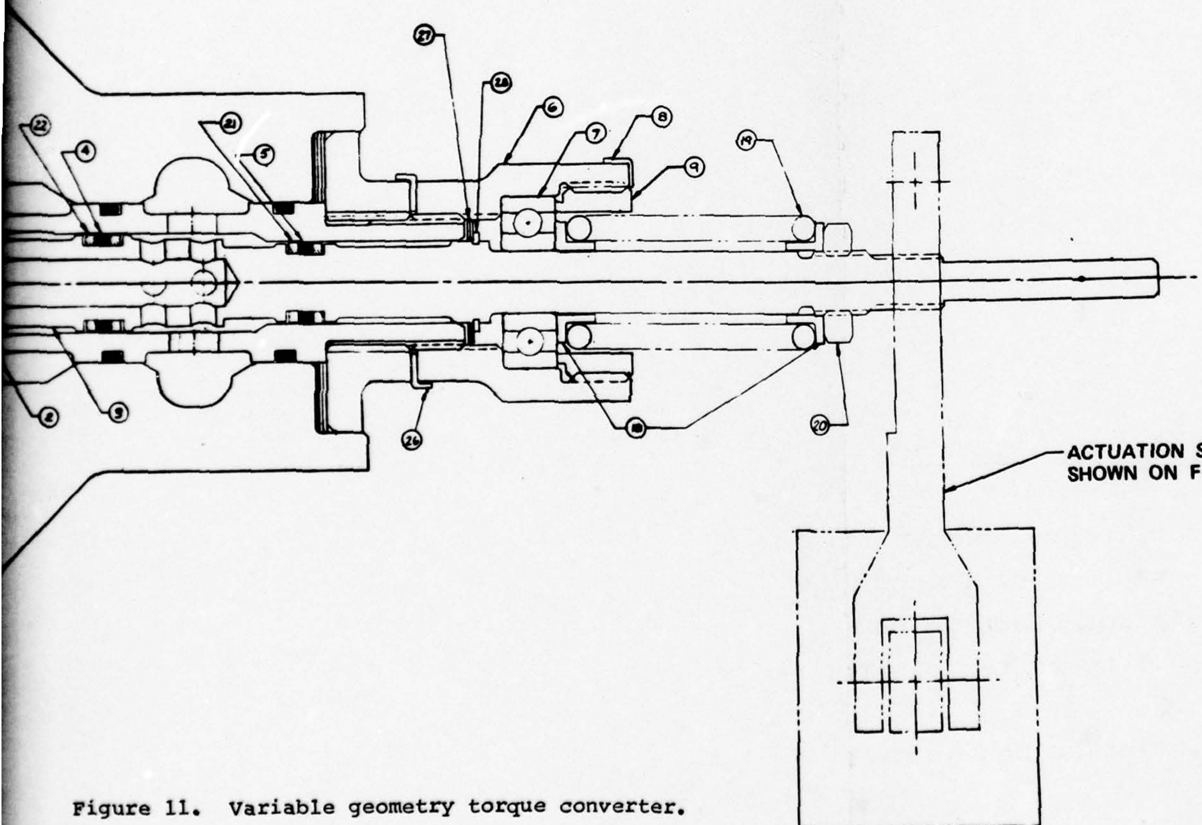


Figure 11. Variable geometry torque converter.

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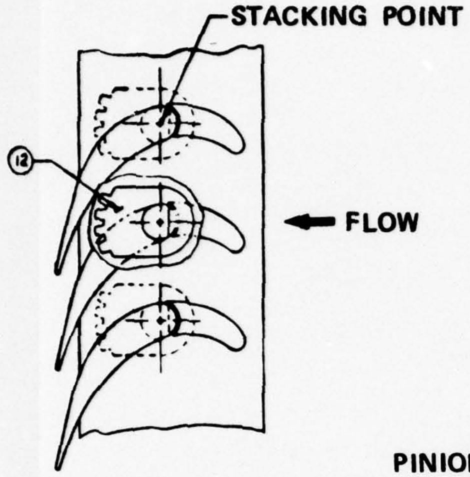
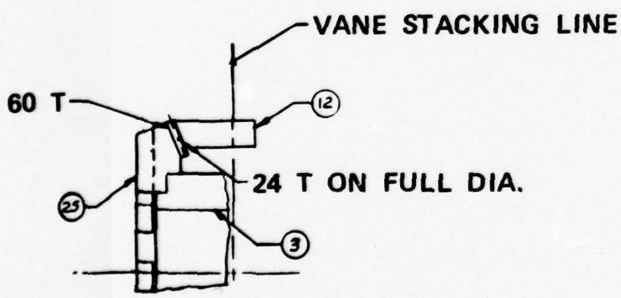
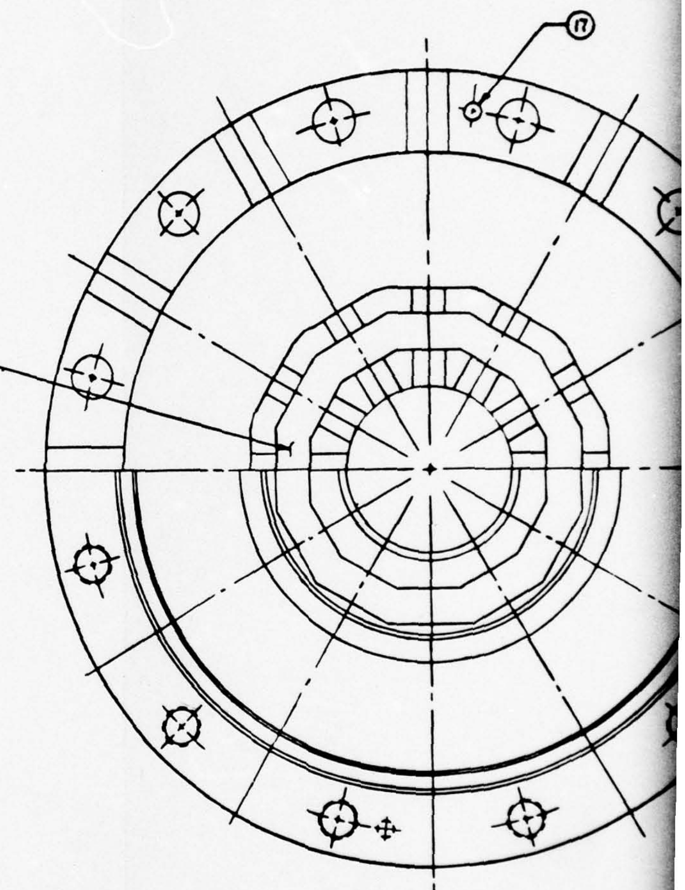


FOLDED OUT VIEW
VANES SHOWN IN NOMINAL POSITION



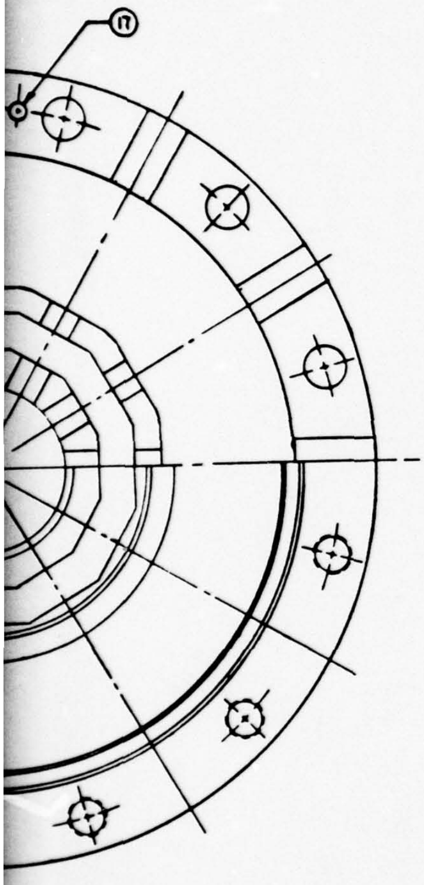
VANE DRIVE GEAR SET



DOWNSTREAM VIEW OF REACTOR WITHOU

NOTE: SEE FIGURE 11 FOR IDENTIFICATION OF FIND NUMBERS.

Figure 12. Variable geometry torque con



EACTOR WITHOUT VANES

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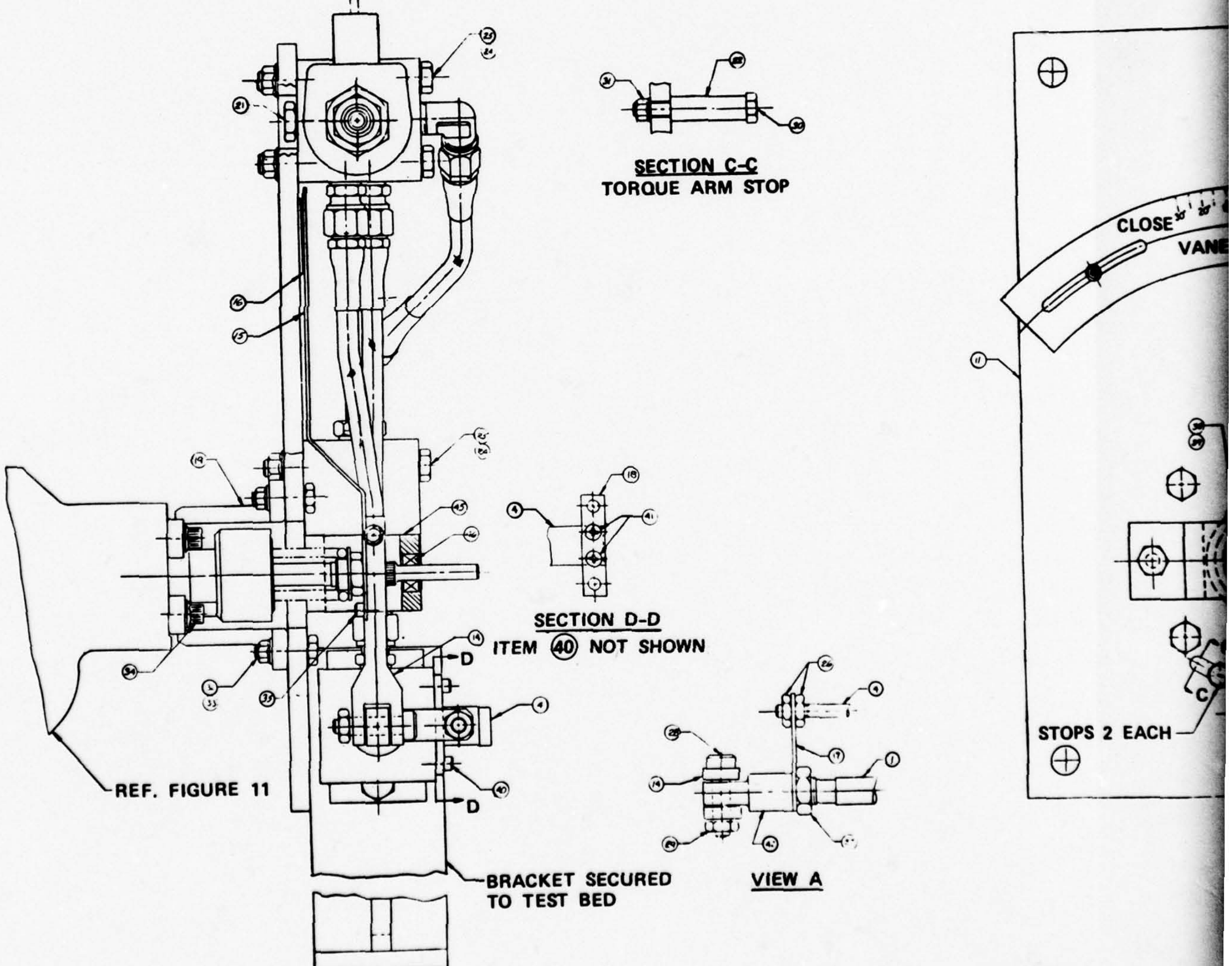
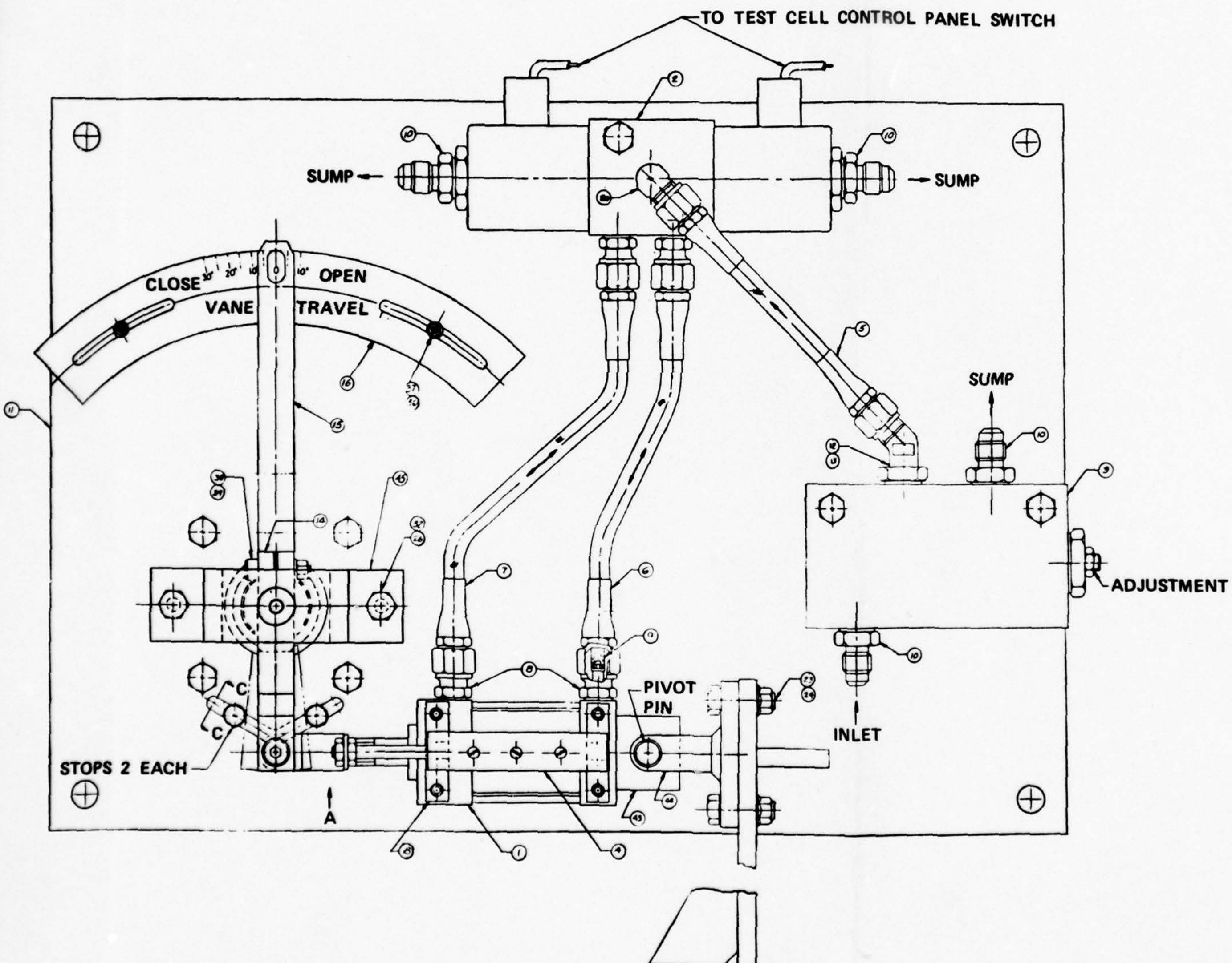


Figure 13. Variabl



FIND NO.	NOM
46	BEAR
45	SUPPO
44	CLEV
43	CLEV
42	ROD
41	SCREW
40	SCREW
39	NUT
38	SCREW
37	SCREW
36	NUT
35	SCREW
34	BOLT
33	NUT
32	BOLT
31	NUT
30	BOLT
29	NUT
28	BOLT,
27	NUT
26	NUT
25	BOLT
24	NUT
23	BOLT
22	SPAC
21	PLUG
20	ELBO
19	BRAC
18	STRA
17	PLAT
16	DIAL
15	POIN
14	TOR
13	RED
12	NIPP
11	INTE
10	NIPP
9	RES
8	NIPP
7	HO
6	HO
5	HO
4	PO
3	VAL
2	VAL
1	CYL

Figure 13. Variable geometry torque converter actuation system.

2

NO.	NOMENCLATURE
	BEARING
	SUPPORT, BRG.
	CLEVIS BRACKET
	CLEVIS
	ROD EYE
	SCREW, F'H'
	SCREW
	NUT
	SCREW
	SCREW
	NUT
	SCREW
	BOLT
	NUT
	BOLT
	NUT
	BOLT
	NUT
	BOLT, SHOULDER
	NUT
	NUT
	BOLT
	NUT
	BOLT
	SPACER
	PLUG - PIPE - 1/4
	ELBOW
	BRACKET - SUPPORT
	STRAP
	PLATE
	DIAL
	POINTER
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	REDUCER
	NIPPLE
	INTERFACE PANEL
	NIPPLE
	RESTRICTOR
	NIPPLE
	HOSE FLEX
	HOSE FLEX
	HOSE, FLEX
	POSITION TRANSMITTER
	VALVE, REG. & RELIEF
	VALVE, 4-WAY-SOLENOID
	CYLINDER, MIDGET

25

3

horsepower and relative flow range are shown in Figure 14, from which the following are noted:

- o Pump input horsepower increases approximately linearly with respect to reactor exit angle.

- o Turbine output horsepower, hence output torque, increases parabolically with reactor exit angle and peaks at an angle of 58 degrees.

- o Flow rate increases as the reactor opens.

Mean flow vector diagrams, for various reactor exit angle settings ranging from 3.0 to 58.0 degrees, were computed from the modified Lucas Program. Vector diagrams for a 28 degree reactor exit angle, which corresponds to 120 horsepower input for the current B-1 torque converter, are shown in Figure 15.

Since the Lucas Program does not recognize geometric effects such as vane thickness blockage, flow path slopes and curvatures, and flow boundary layer separation, interpreting and utilizing the above results requires more understanding of flow geometry in the design under consideration. For example, B-1 torque converter development test data (Figure 16) indicated that the pump inlet horsepower, at 0.1 speed ratio, remained nearly unchanged as the reactor exit angle opened from 28 to 42 degrees. A close examination of the reactor geometry revealed that due to the highly cambered reactor vane, the inlet flow path was throttled rapidly as the exit opened (see Figure 17). Consequently, the expected flow rate increases did not occur. This throttling could be minimized by using an articulated vane, or redefining the reactor thickness distribution to favor high horsepower.

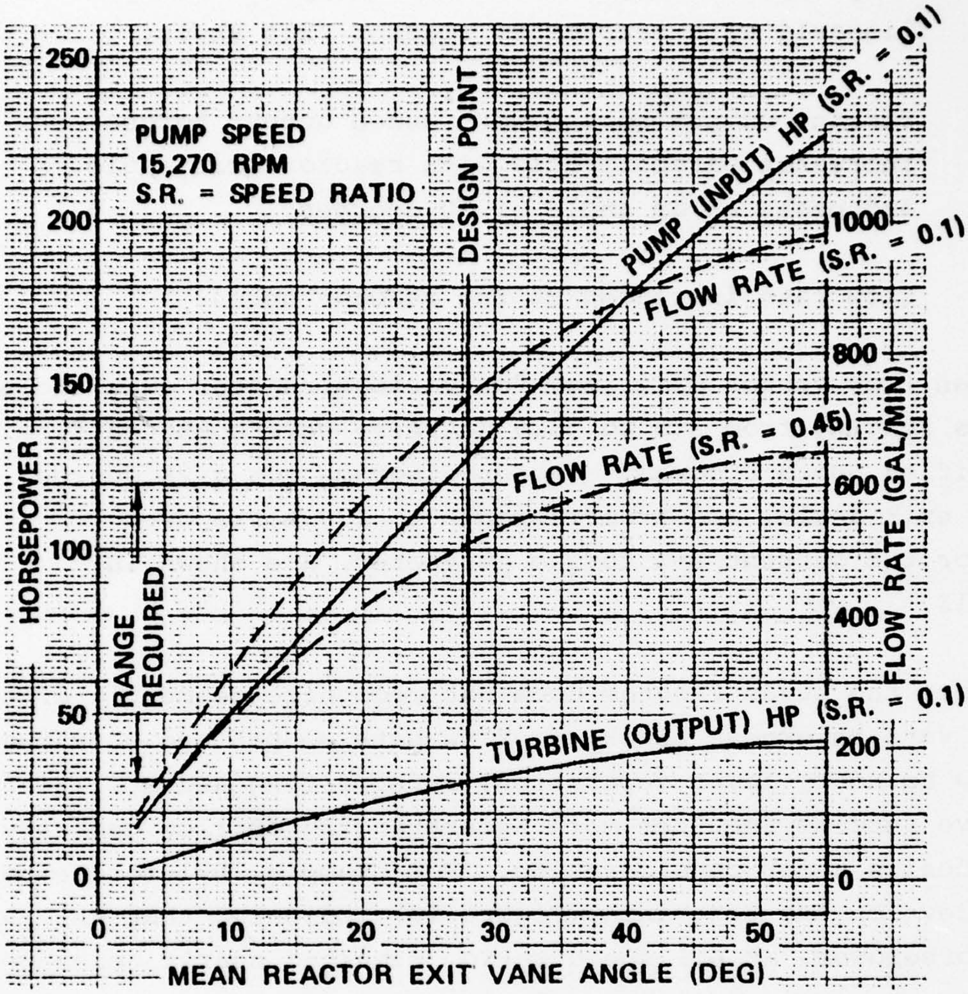


Figure 14. Variable reactor torque converter performance prediction.

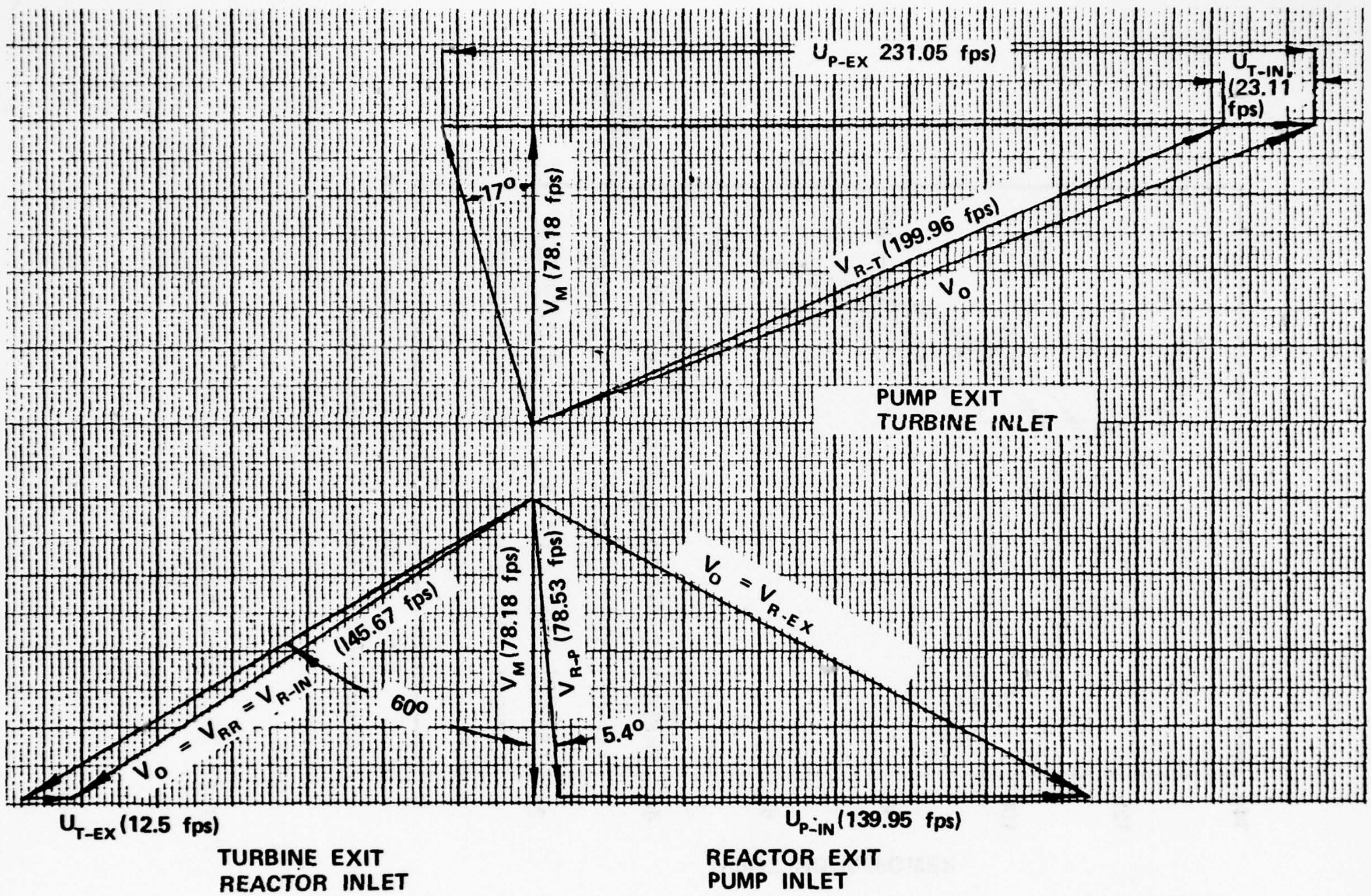


Figure 15. B-1 torque converter vector diagram β_{R-EX} = 28° S.R. = 0.1.

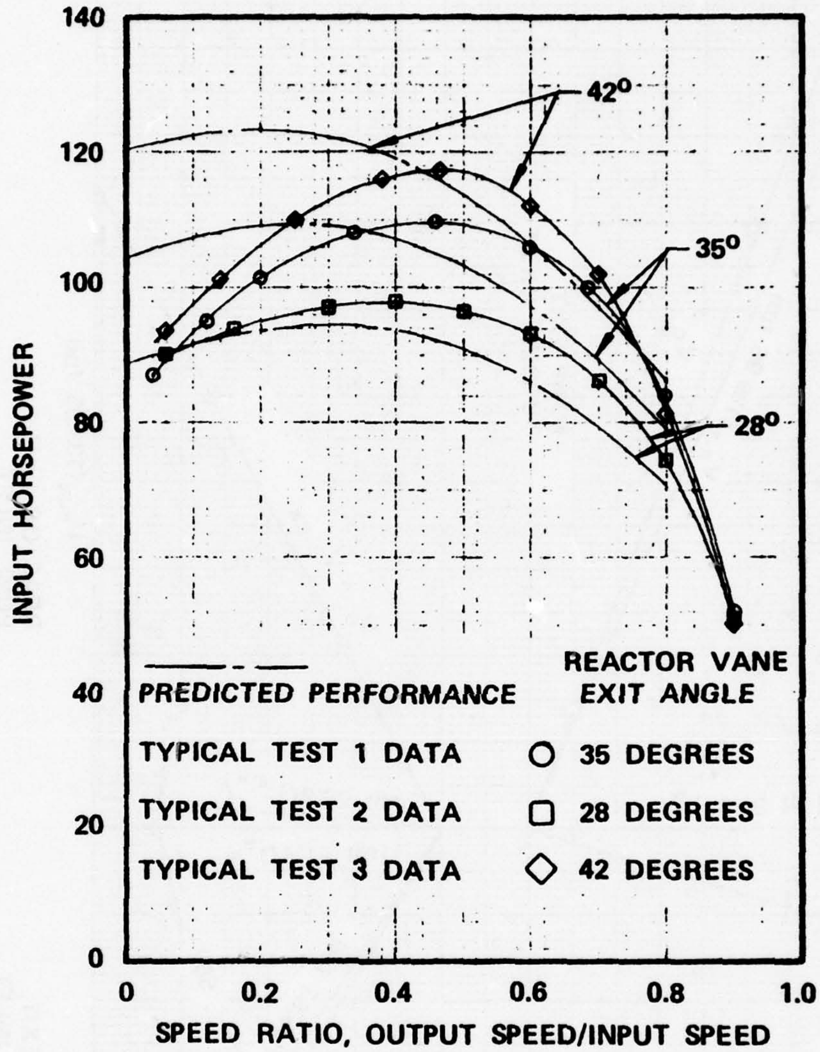


Figure 16. B-1 torque converter test data.

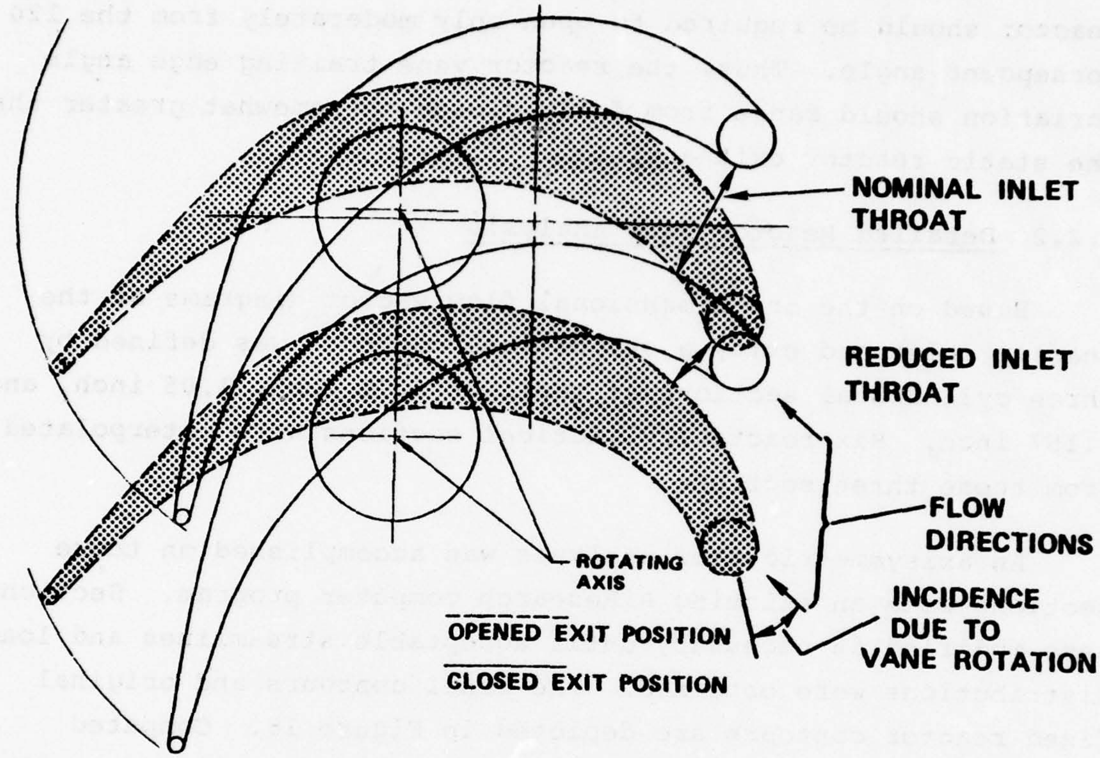


Figure 17. Illustration of throttling effect due to integral vane rotation.

For the geometrical restraints of the B-1 configuration, a reactor capable of opening (or increasing horsepower) from the required 120 horsepower point would increase geometry complexities and/or compromise performance at lower power inputs. It was therefore concluded that for this program, the variable reactor should be required to open only moderately from the 120 horsepower angle. Thus, the reactor vane trailing edge angle variation should range from fully closed to somewhat greater than the static reactor exit angle.

2.2.2 Detailed Reactor Vane Analysis

Based on the one-dimensional flow vector diagrams at the reactor inlet and exit, a set of vane contours was defined by three cylindrical sections at radii of 0.71 inch, 1.05 inch, and 1.157 inch. Six reactor cylindrical sections were interpolated from these three sections.

An axisymmetric flow analysis was accomplished on these sections with an existing AiResearch computer program. Sections were modified as necessary until acceptable streamlines and load distributions were obtained. The final contours and original fixed reactor contours are depicted in Figure 18. Computed streamlines for the final vane contours are shown in Figure 19. The smooth streamline shape indicates no sudden flow discontinuities; thus, no excessive pressure loss should occur. Note that streamline variations through the vane are dependent on the vane geometry, while those upstream and downstream of the vane remain nearly unchanged with changes in vane design. Final hub and shroud vane velocity distributions (loadings) for design-point conditions are presented in Figure 20.

Final vector diagrams for the shroud, mean and hub streamlines at the reactor inlet and exit are shown in Figures 21 and 22, respectively. The one-dimensional vector diagrams are also shown. It is clear that, as the slope, curvature and blade thickness effects were taken into account in the axisymmetric analysis, the vector diagrams changed significantly.

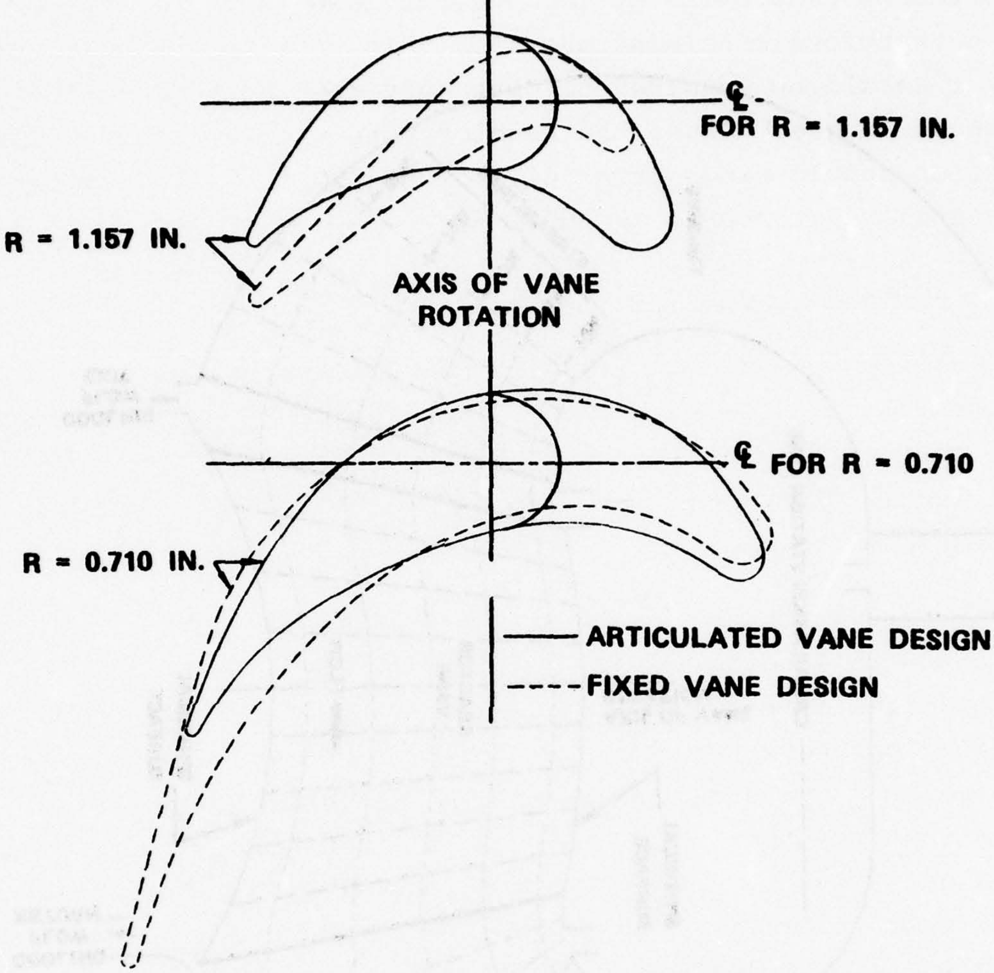


Figure 18. Torque converter reactor vane cylindrical section comparison.

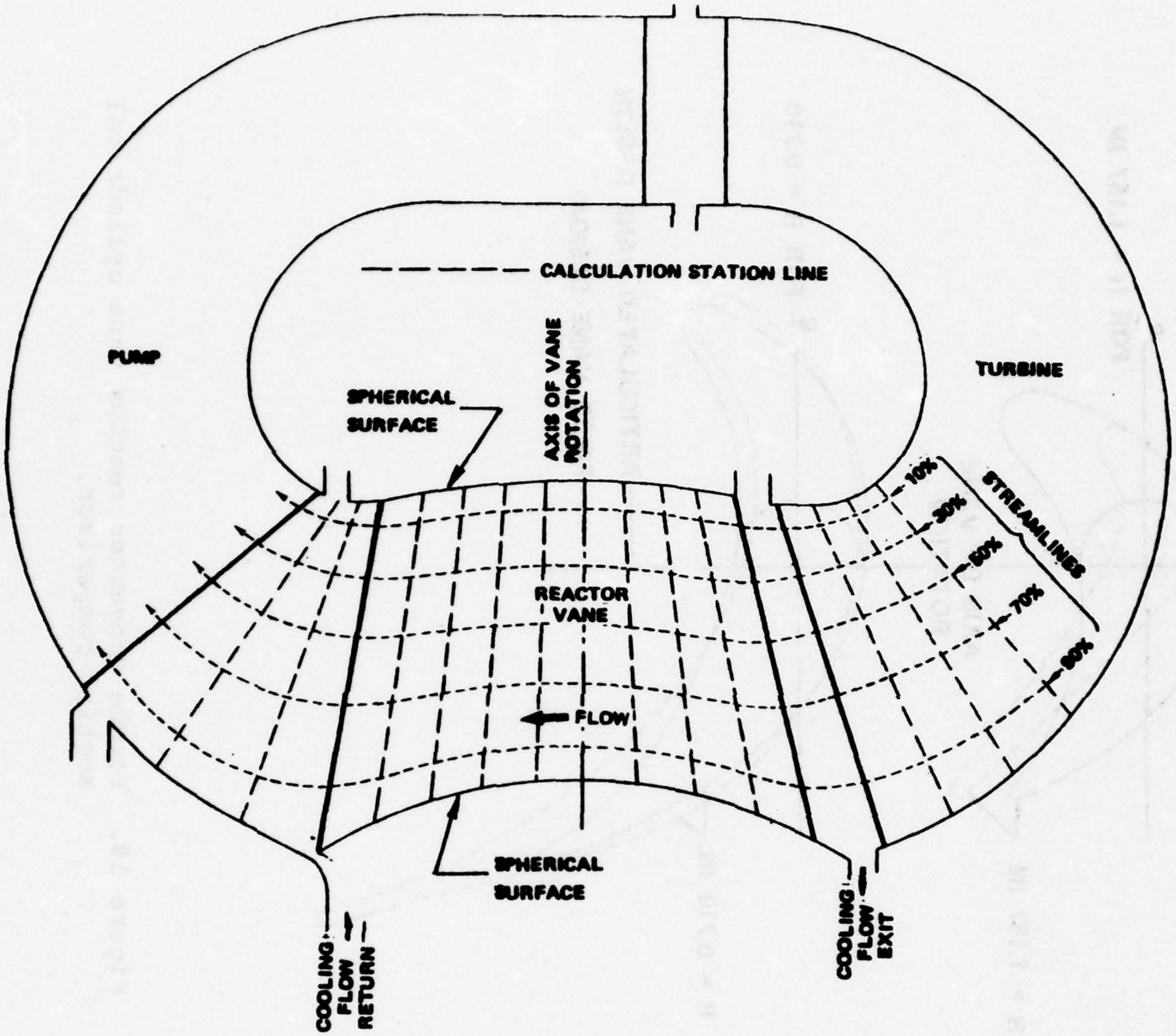


Figure 19. Variable reactor torque converter flow path and streamline distribution.

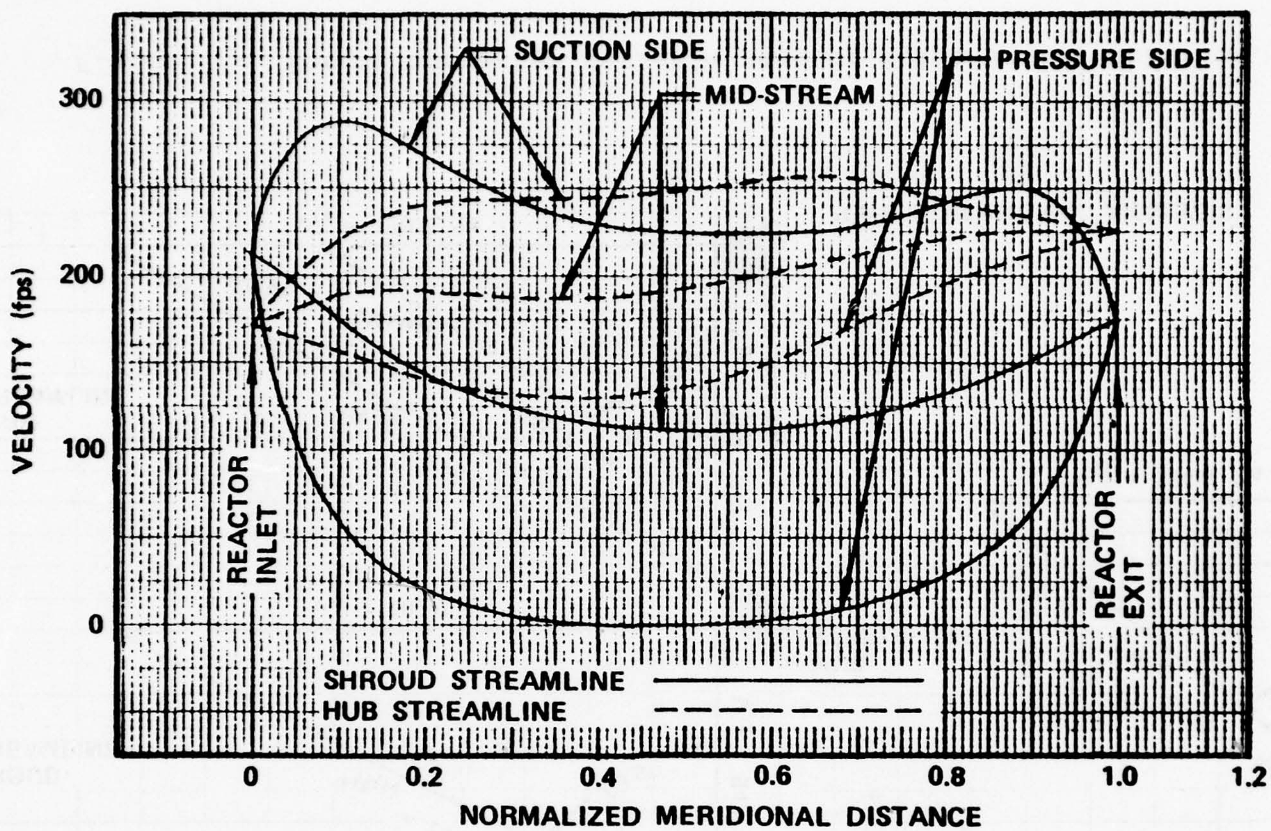


Figure 20. Torque converter variable reactor velocity distributions.

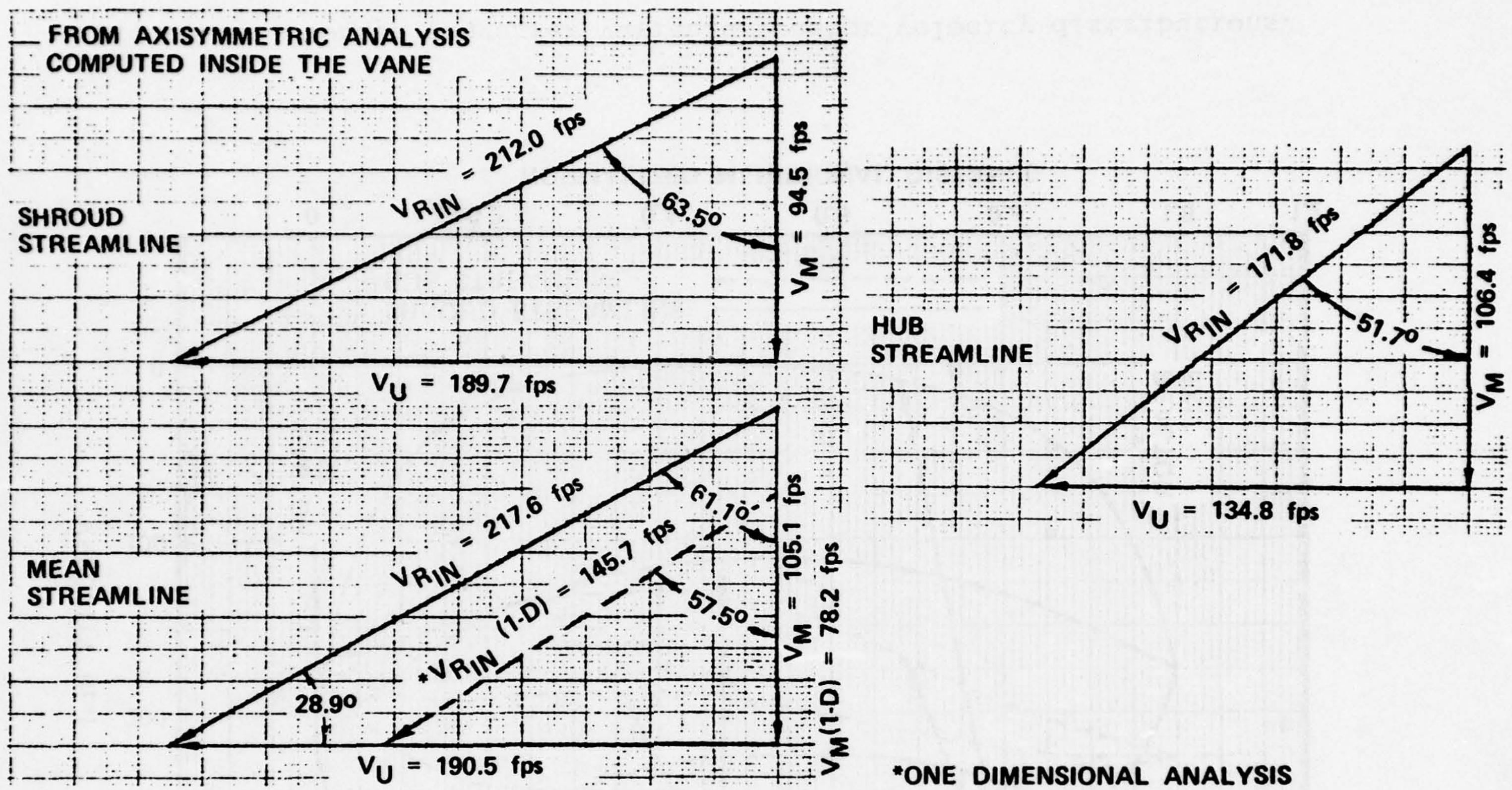


Figure 21. Torque converter variable reactor inlet vector diagrams.

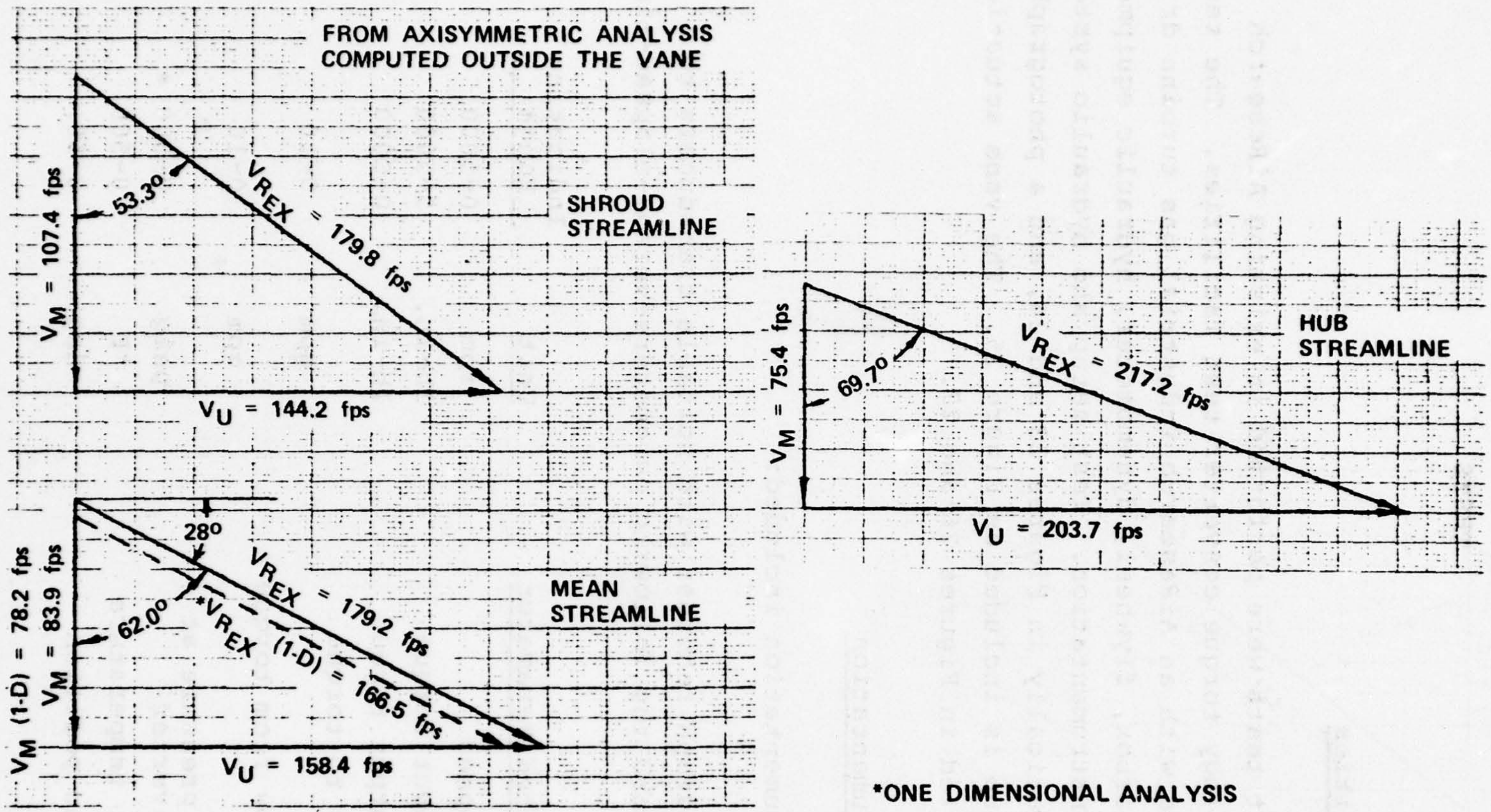


Figure 22. Torque converter variable reactor exit vector diagrams.

SECTION III
TESTS

3.1 Test Facilities

Development tests were performed in existing AiResearch advanced technology torque converter test facilities. The test cell is equipped with an AiResearch industrial gas turbine drive engine, test gearbox, flywheel, dynamometer, hydraulic equipment and necessary instrumentation. Test setup and hydraulic system are shown schematically in Figures 23 and 24, and a photograph of the test setup is included as Figure 25. The vane actuation system is depicted in Figures 26 and 27.

3.2 Test Instrumentation

Test instrumentation included:

An oscillograph recorder with suitable transducers to measure and record the following parameters-versus-elapsed-time:

Measured Parameter	Unit	Indicating Range
Flywheel speed	rpm	0-5000
Gearbox input torque	lb-in.	0-5000
Gearbox output torque	lb-in.	0-5000
Input flow to torque converter	gpm	0-10
Output flow from torque converter	gpm	0-10
Input oil pressure at torque converter	psig	0-500
Output oil temperature	°F	0-500
Stator vane position	deg	0-50

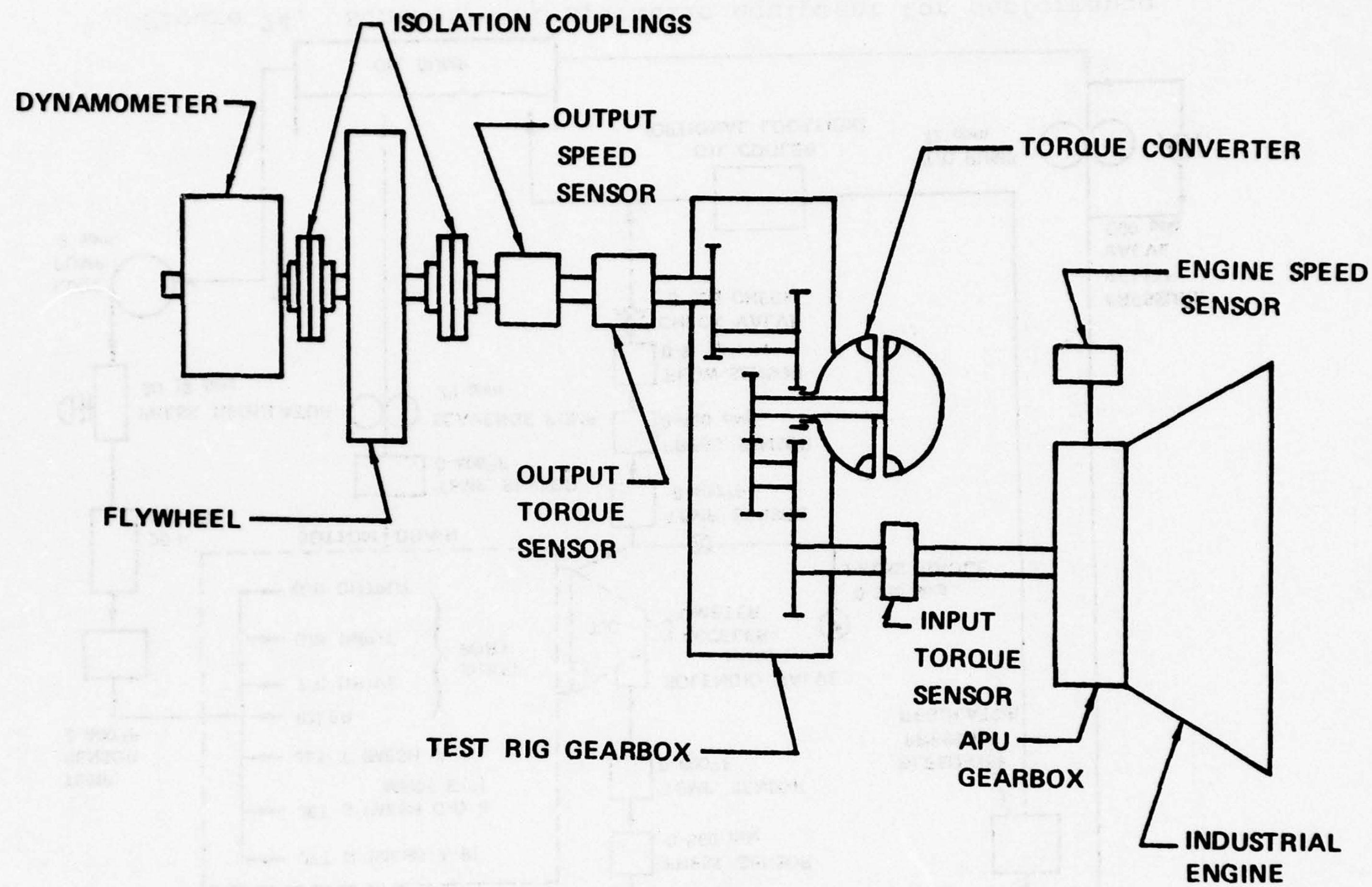


Figure 23. Schematic of mechanical equipment for performance testing torque converters.

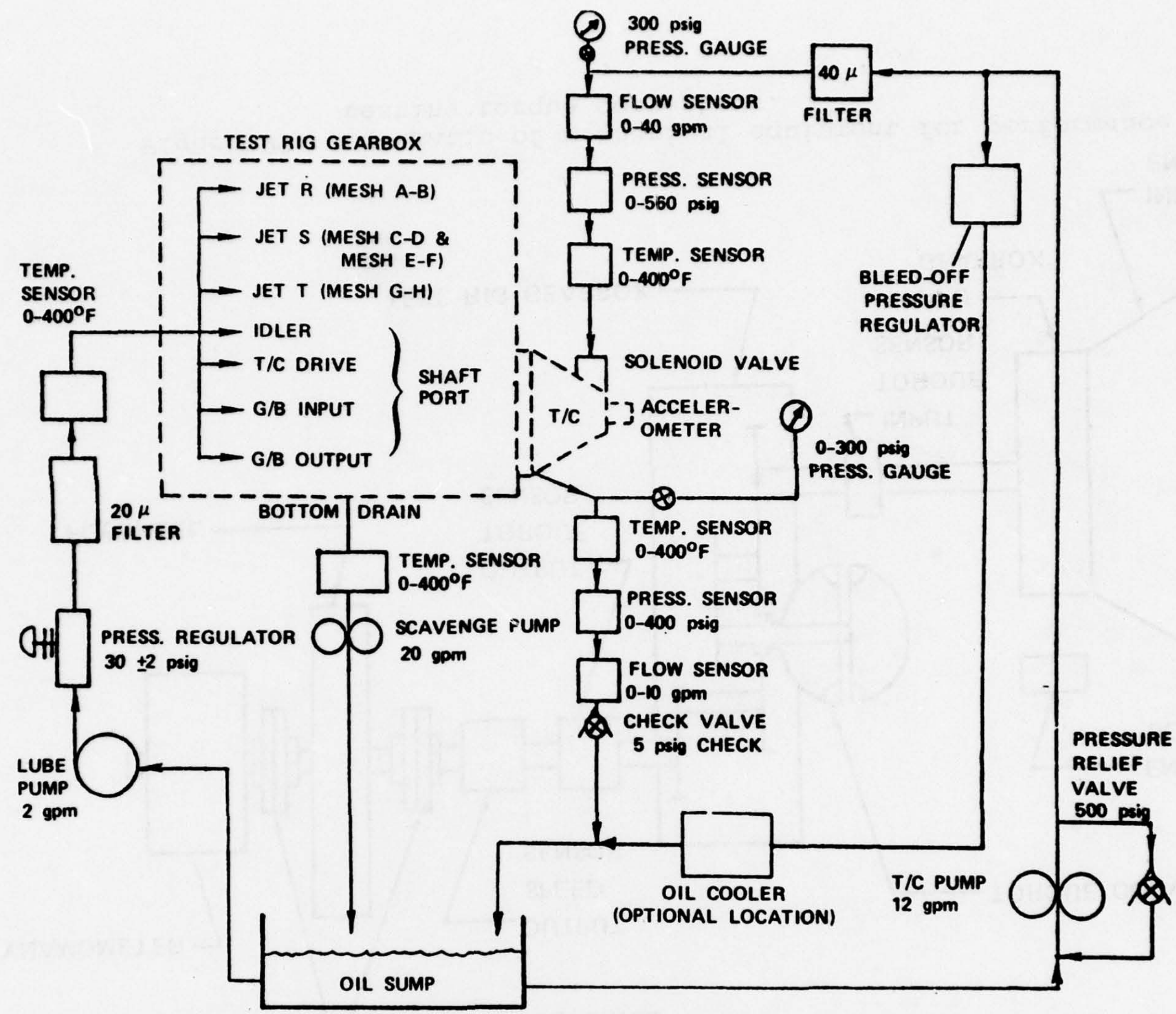


Figure 24. Schematic of hydraulic equipment for performance testing torque converters.

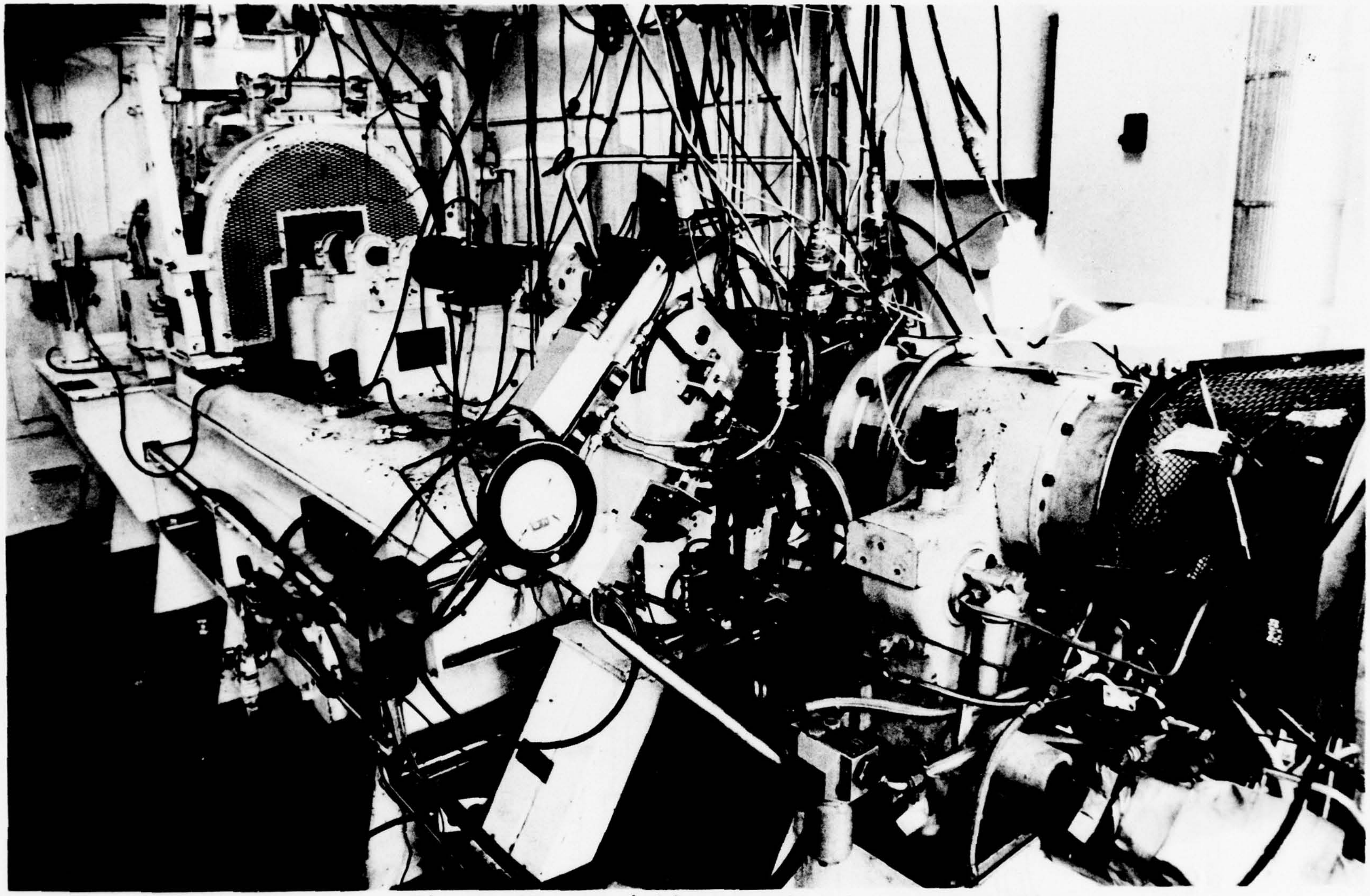


Figure 25. Variable geometry torque converter test setup.

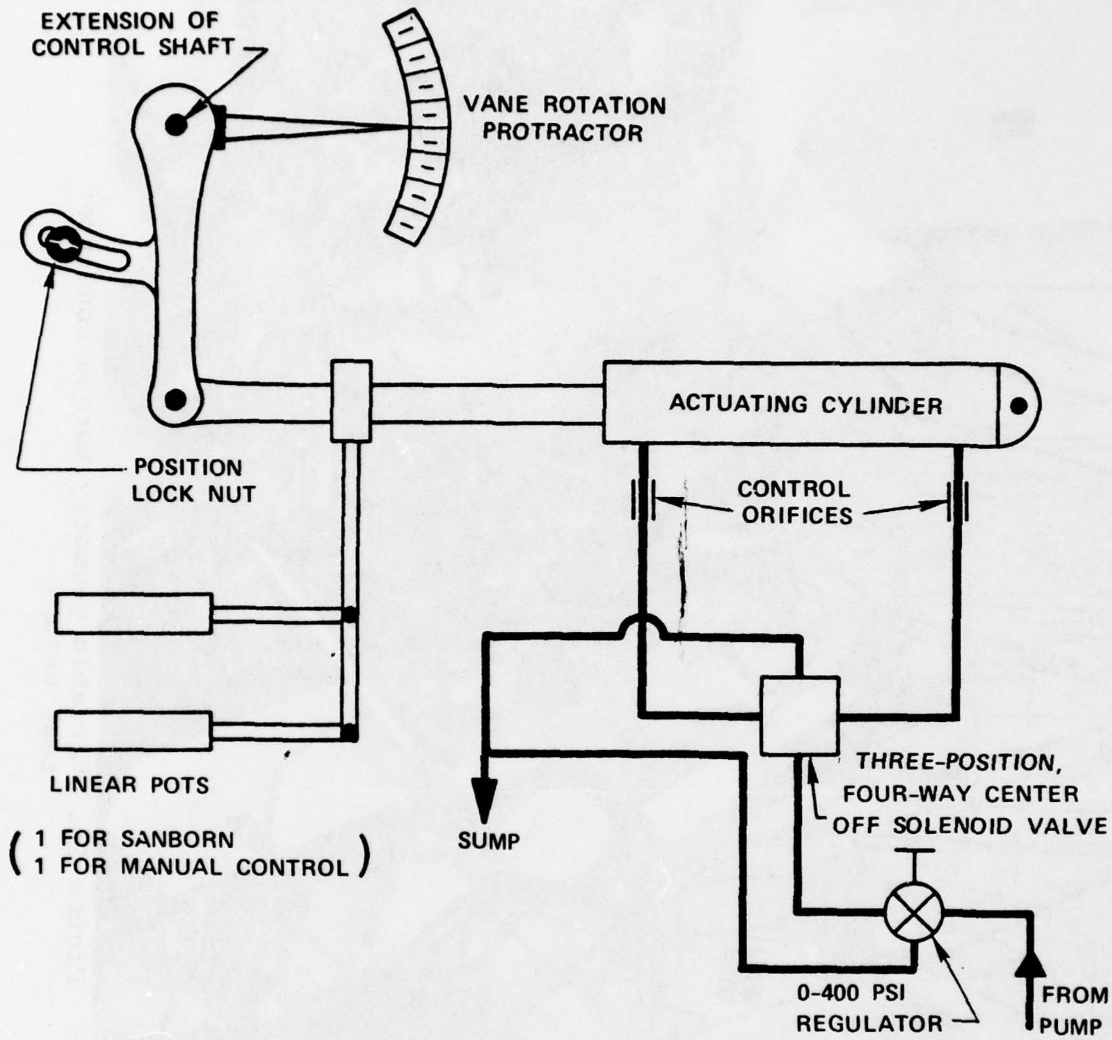


Figure 26. Schematic of vane actuating equipment for controlling capacity of variable geometry torque converter.

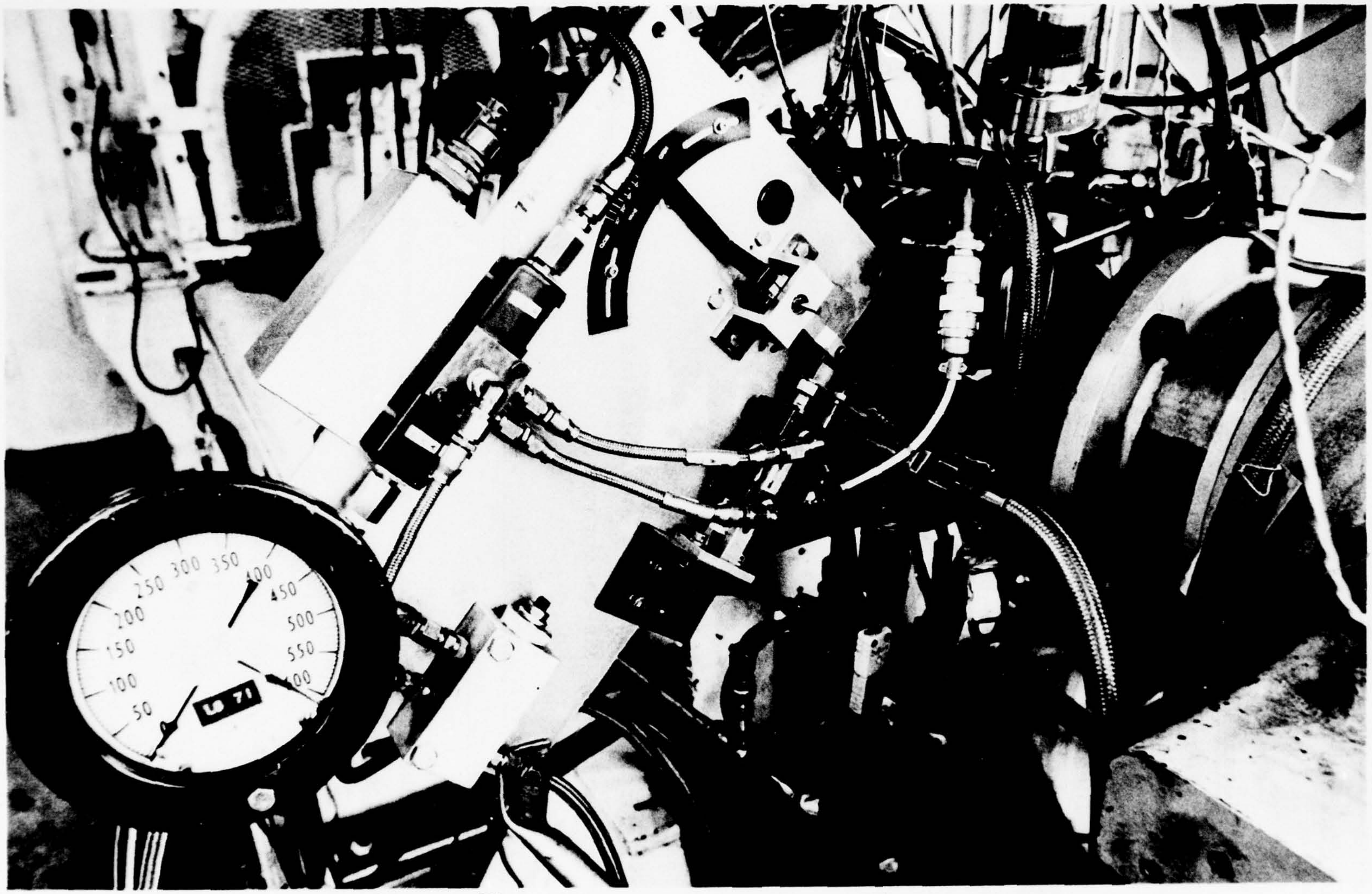


Figure 27. Test setup, vane actuation system.

In addition, the following data were transmitted to a remote digital recording system:

Measured Parameter	Unit	Indicating Range
Engine speed	rpm	0-40,000
Gearbox input torque	lb-in.	0-1000
Input oil temperature	°F	0-200
Time interval indicator	sec	0-60
Vibration amplitude on torque converter housing	mil	0-2
Outer case temperature at rear flange	°F	0-200

Data from this instrumentation were acquired at a rate of five complete recordings per second.

3.3 Test Procedure

3.3.1 Calibration

The torque converter was assembled as a standard B-1 unit. All instrumentation was calibrated.

3.3.2 Tests on Torque Converter with Fixed Reactor Blades (Baseline Test)

Individual tests were performed with inlet pressures set at 500, 450, 400, 350, and 300 psig, according to the following steps:

(a) Gearbox lube oil pressure set at 35 ±5 psig and the torque converter inlet oil pressure at the set pressure ±10 psi.

(b) Engine started and speed stabilized at 38,690 rpm; for 10 min.

(c) Vibration amplitude on the torque converter housing was measured and recorded. The housing temperature was measured in the same zone on the housing, and recorded.

(d) The recorder was started (1 cm/sec), the flywheel brake released, and the solenoid valve was opened to fill the torque converter flowpath. After a 30-sec acceleration, the parameters listed on the data sheet were manually recorded.

NOTE

Runs were repeated at the various inlet pressures to establish the pressure where cavitation became objectionable and affected performance.

3.3.3 <u>Preliminary Integrity Tests on VGTC Unit With Stator Vanes Locked at 0° and at 7° Closed</u>

The reactor was removed and replaced with the variable reactor components. The angular position of the reactor actuator shaft was marked so that at the 0-degree reference on this shaft (protractor reading) the vanes were positioned identical to the position of the fixed reactor vanes in the B-1 unit.

(a) Tests of Paragraph 3.3.2 were repeated on the variable reactor unit.

(b) The unit was disassembled, and the reactor inspected for changes occurring during the tests. Photographs were taken before and after these tests, and are included in the discussion of test results.

3.3.4 Fixed-Vane Position Test Runs on VGTC Unit

(a) The preliminary test procedure defined in Paragraph 3.3.3 at 0° setting and the selected inlet pressures was repeated.

(b) The actuator shaft was rotated to advance the articulated blades (closing) 2.5°, as measured at the protractor on the test fixture. The blades were locked in this position and the test was repeated. This procedure was repeated until the blades reached their maximum closed position (27.5°).

3.3.5 Preliminary VGTC Unit Modulation Tests

The vane control shaft was connected to the actuator control systems (Figure 26). With the control pressure regulator set at 100 psig, preliminary timing runs were made to establish the control orifice sizes required to full-stroke the actuator shaft.

3.3.5.1 Modulated Vane Position Test Runs

(a) 0° to 27.5° Stroke (Open to Closed) in 20 Sec - Orifices were installed to give a 20-sec time delay for full stroke of the vane control shaft. The control solenoid was energized with a one-sec delay after actuation of the torque converter oil input solenoid, and the procedure for a preliminary test run repeated. The control was deenergized after 20 sec and data was recorded.

(b) 0° to 27.5° Stroke (Open to Closed) in 15 Sec - Step (a) was repeated with control orifices suitable for 15-sec runs.

(c) 27.5° to 0° Stroke (Closed to Open) in 20 Sec - Step (a) was repeated, starting from the full-closed position.

(d) 27.5° to 0° Stroke (Closed to Open) in 15 Sec - Step (b) was repeated, starting from the full-closed position.

3.3.6 Over-Open Fixed Vane Test

The over-open fixed vane test was performed as follows:

(a) The actuator shaft was rotated 2.5° clockwise and tests performed as described in Paragraph 3.3.4.

(b) Step (a) was repeated at 2.5° intervals until the vanes contacted the shroud.

3.4 Test Components

3.4.1 Baseline Torque Converter with Fixed Vanes

Figures 28 and 29 show the baseline torque converter, assembled and disassembled. This torque converter is in production for the B-1 aircraft secondary power system, and is used to couple the GTCP165 gas turbine engine to the aircraft main engine power takeoff shaft, for starting.

3.4.2 Variable Reactor Torque Converter

Variable reactor components are shown in Figures 30 through 38, as follows:

- Figure 30 - Complete variable reactor, including the actuating arm, damping system, and brackets.

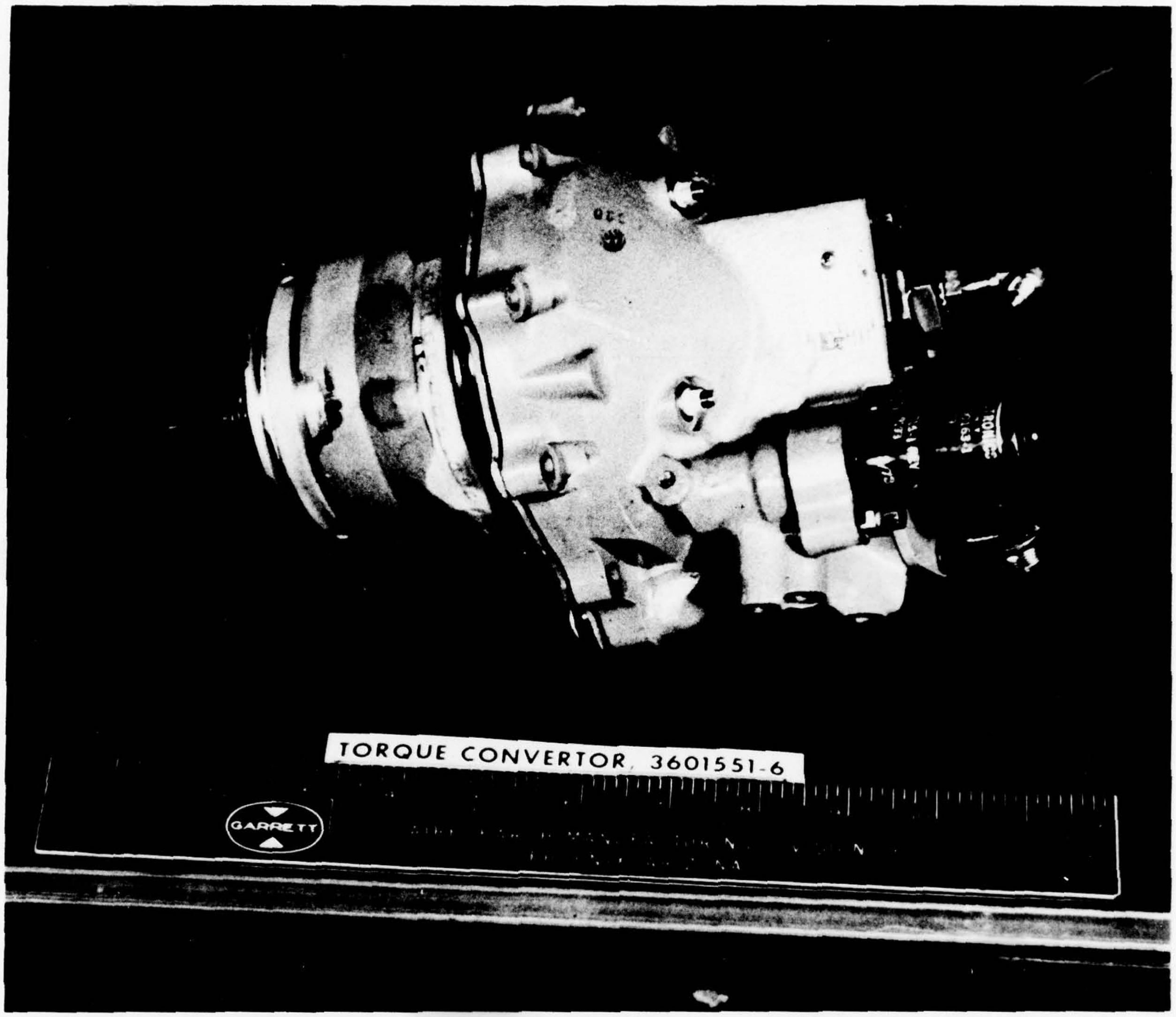


Figure 28. Baseline torque converter--assembled.

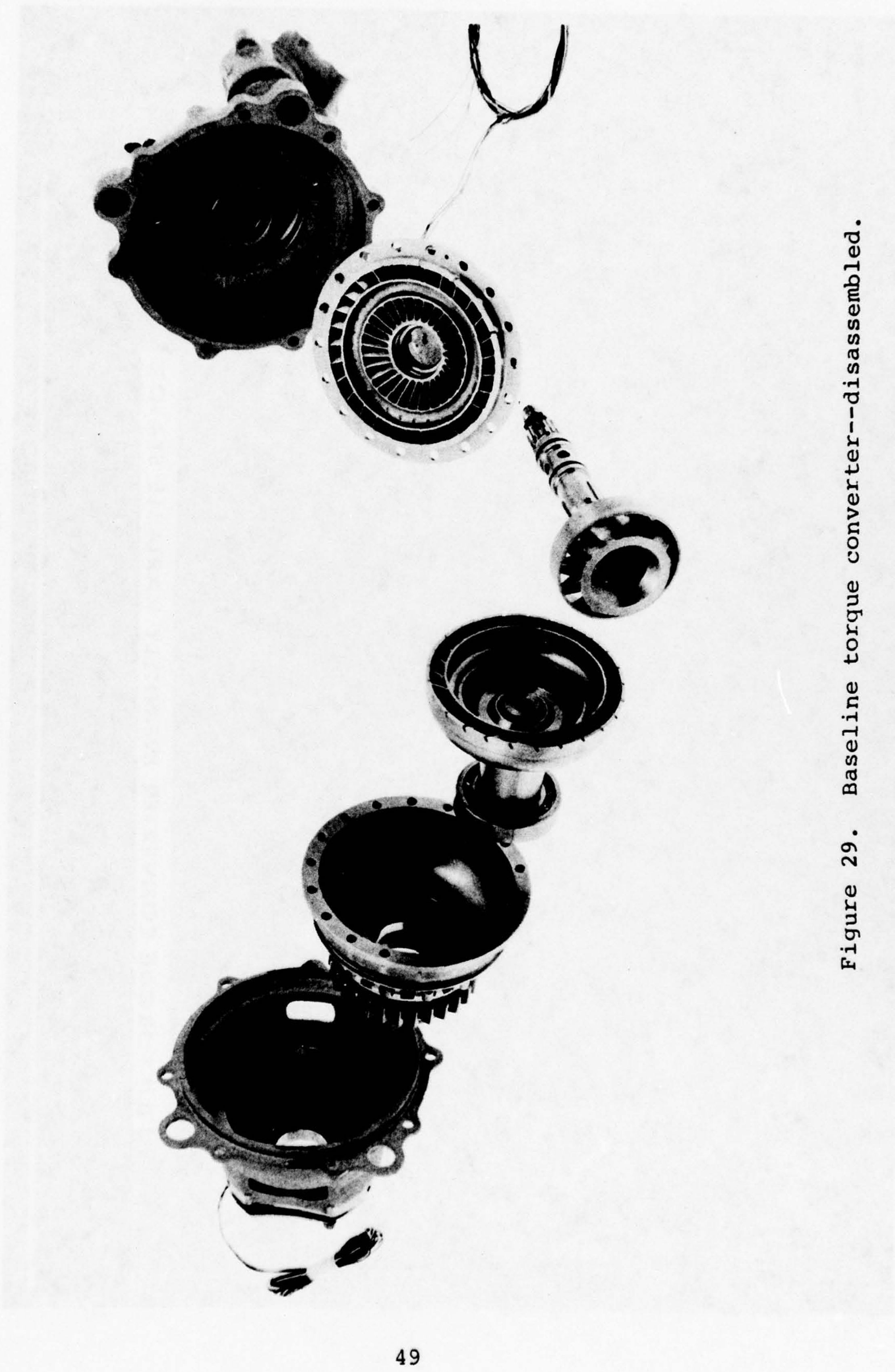


Figure 29. Baseline torque converter--disassembled.

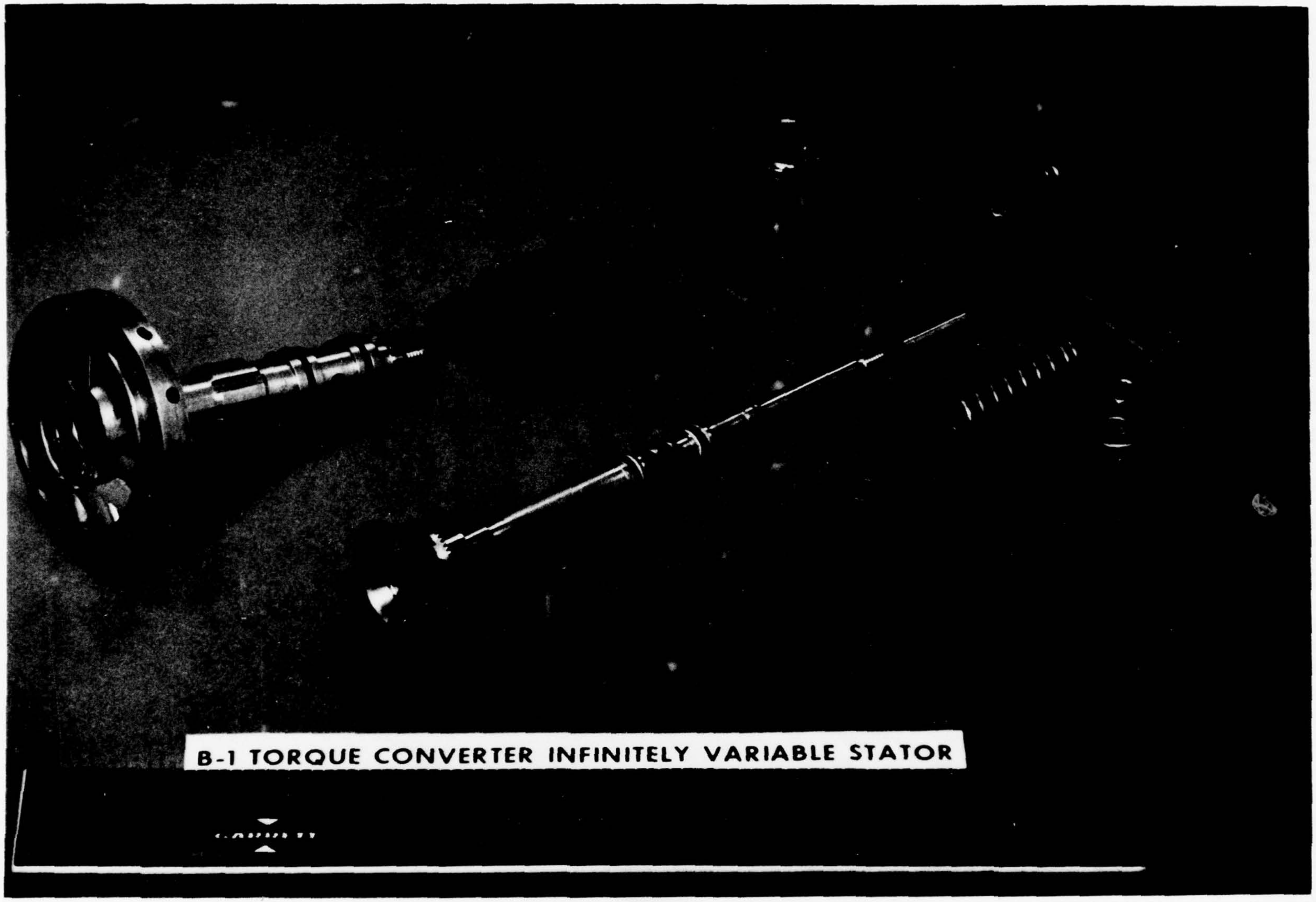


Figure 30. Variable reactor--disassembled.

Figure 31. Variable reactor--forward view.

- Figure 31 - Forward view of the reactor looking in the direction of flow through the static vane section.

- Figure 32 - Rear view of the reactor, variable vane sections removed.

- Figures 33, 34 - Rear view of the reactor showing gear actuation system details.

- Figure 35 - Torque converter major subassemblies. Turbine on left, reactor in center, and impeller on right.

- Figures 36, 37, 38 - Rear view of the reactor with vanes in three actuation positions.

3.4.3 Components after Testing

Torque converter components were examined after completing required testing. No evidence of wear or failure could be detected in any part, with the exception of a heavy polish mark near the pinion gear segment roots. The actual amount of wear was less than 0.0005 inch when examined microscopically. The mark was caused by a plus step on the tooth profile at the tip of the bevel gear teeth, which could only have occurred during manufacturing. It was concluded that the unit was satisfactory for further testing.

3.5 Test Results

3.5.1 Baseline Test Results

As discussed previously, the baseline vehicle was a typical production B-1 torque converter.

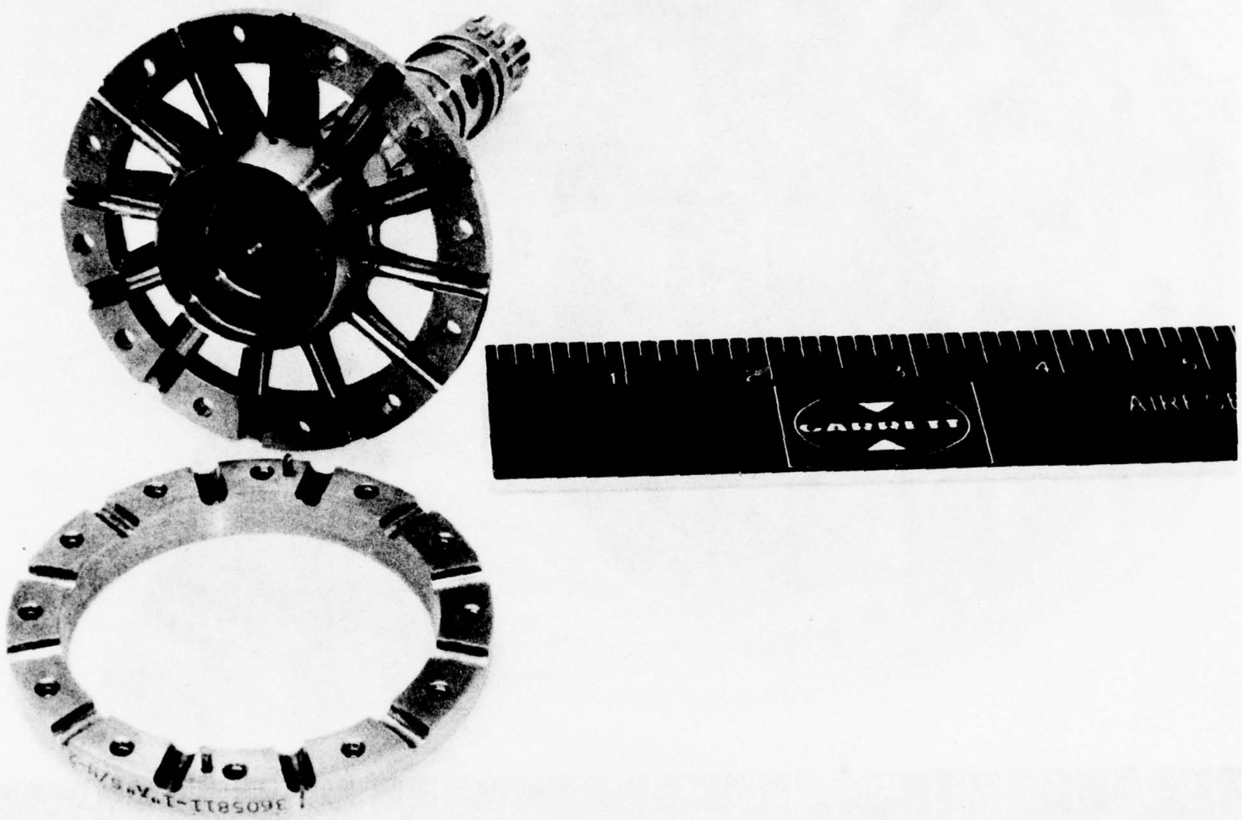


Figure 32. Variable reactor--rear view, variable vane section removed.

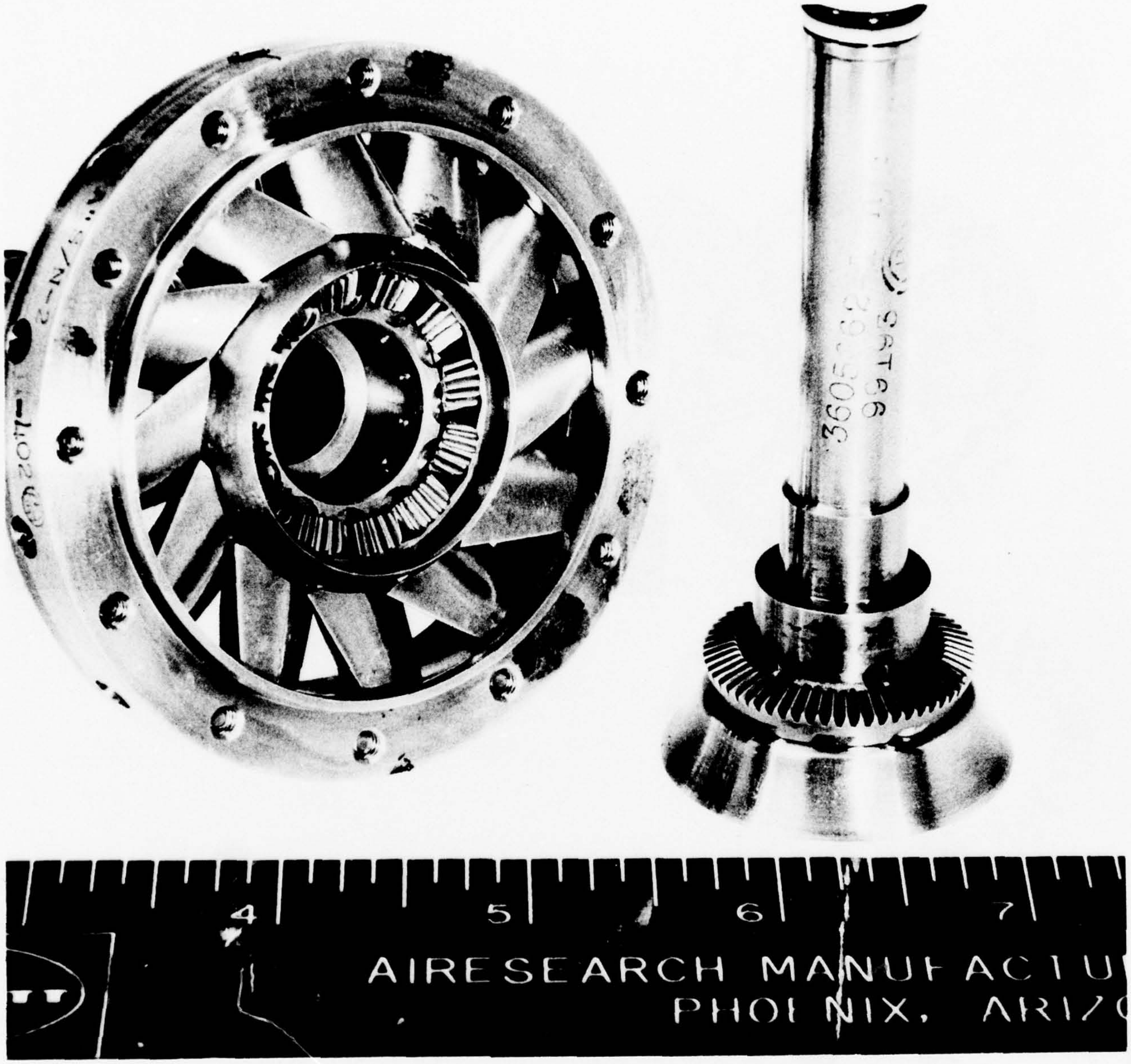


Figure 33. Variable reactor--rear view.

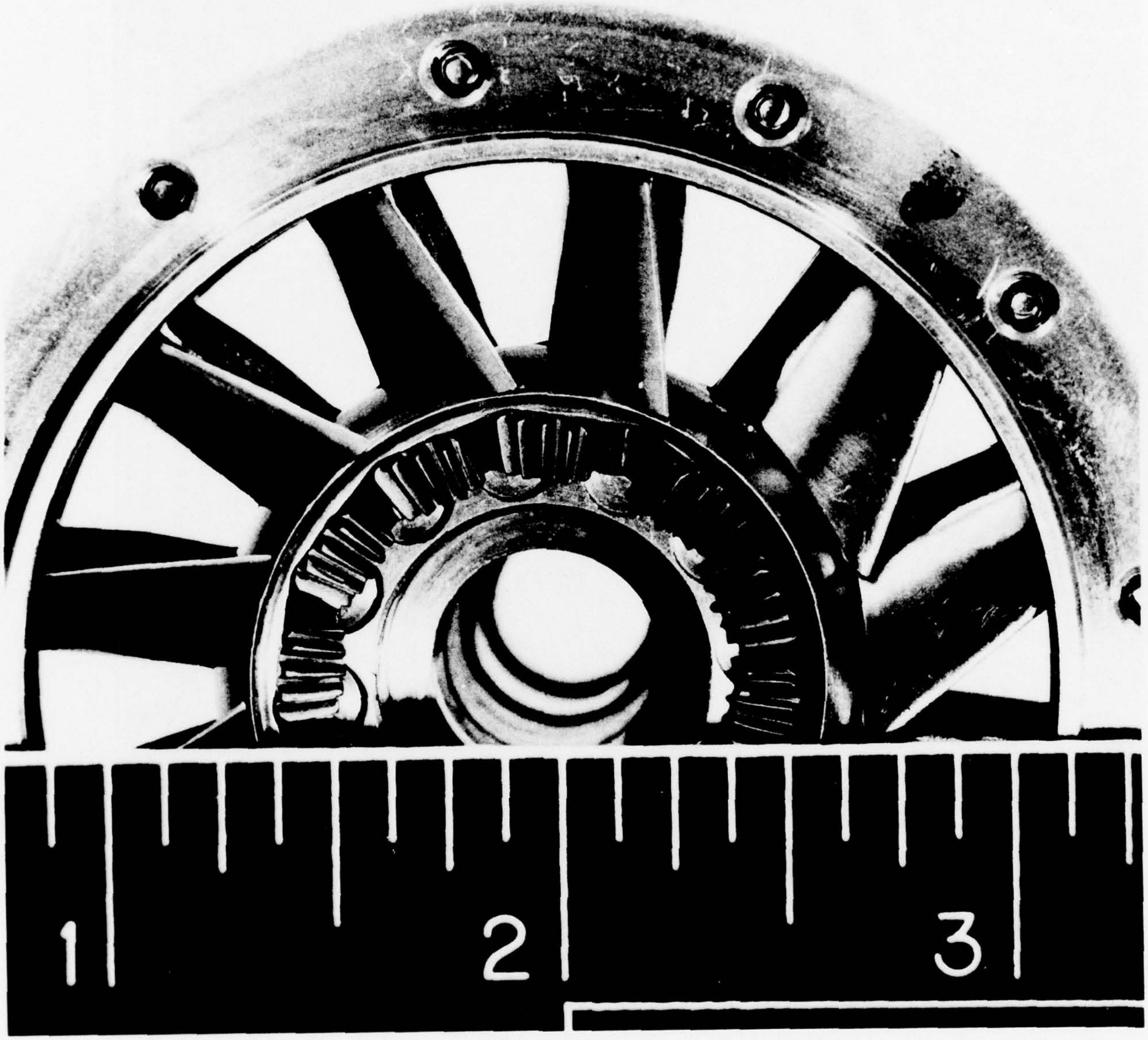


Figure 34. Variable reactor--rear view.

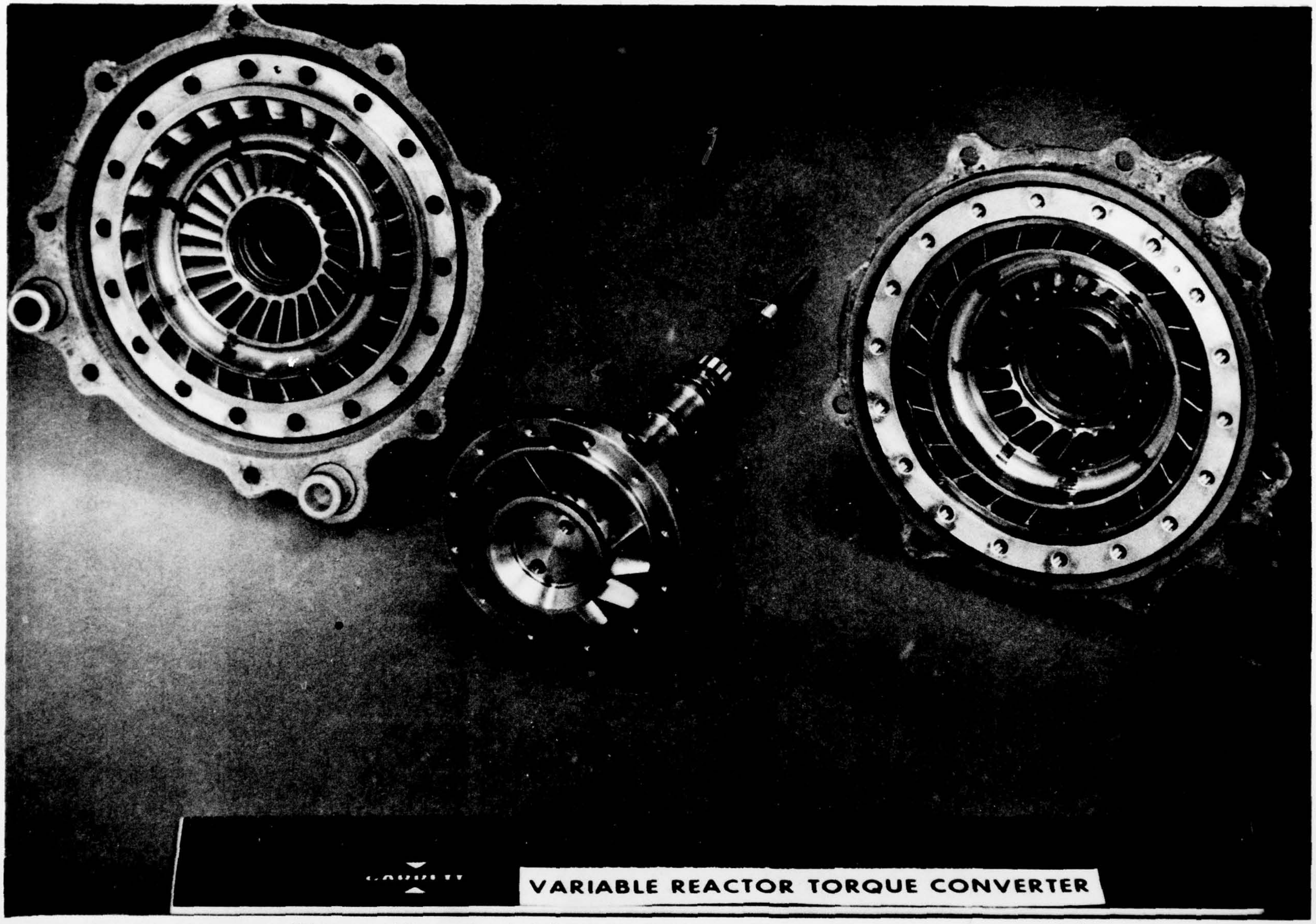


Figure 35. Variable reactor torque converter subassemblies.

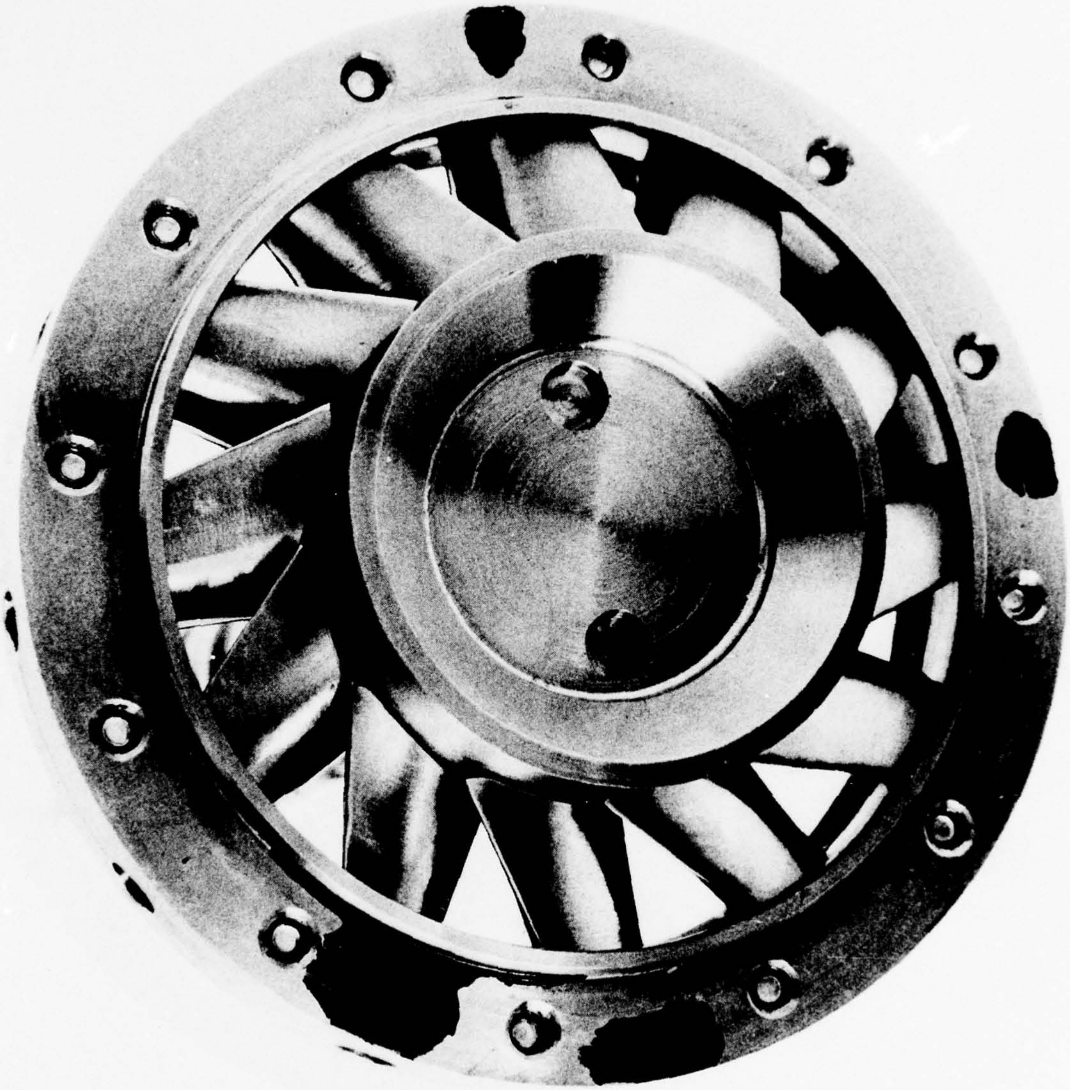


Figure 36. Variable reactor vanes fully closed.

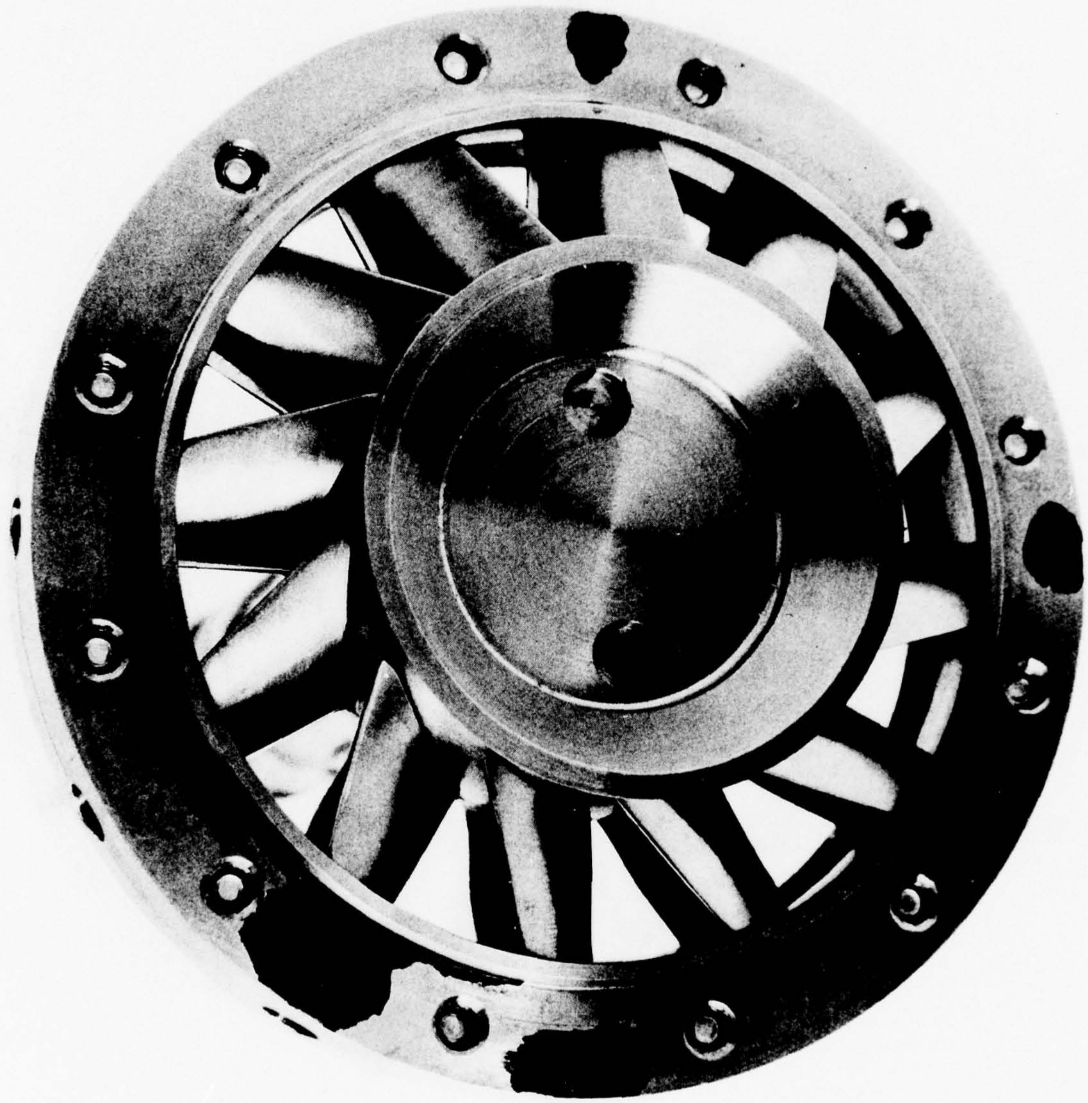


Figure 37. Variable reactor vanes partially open.

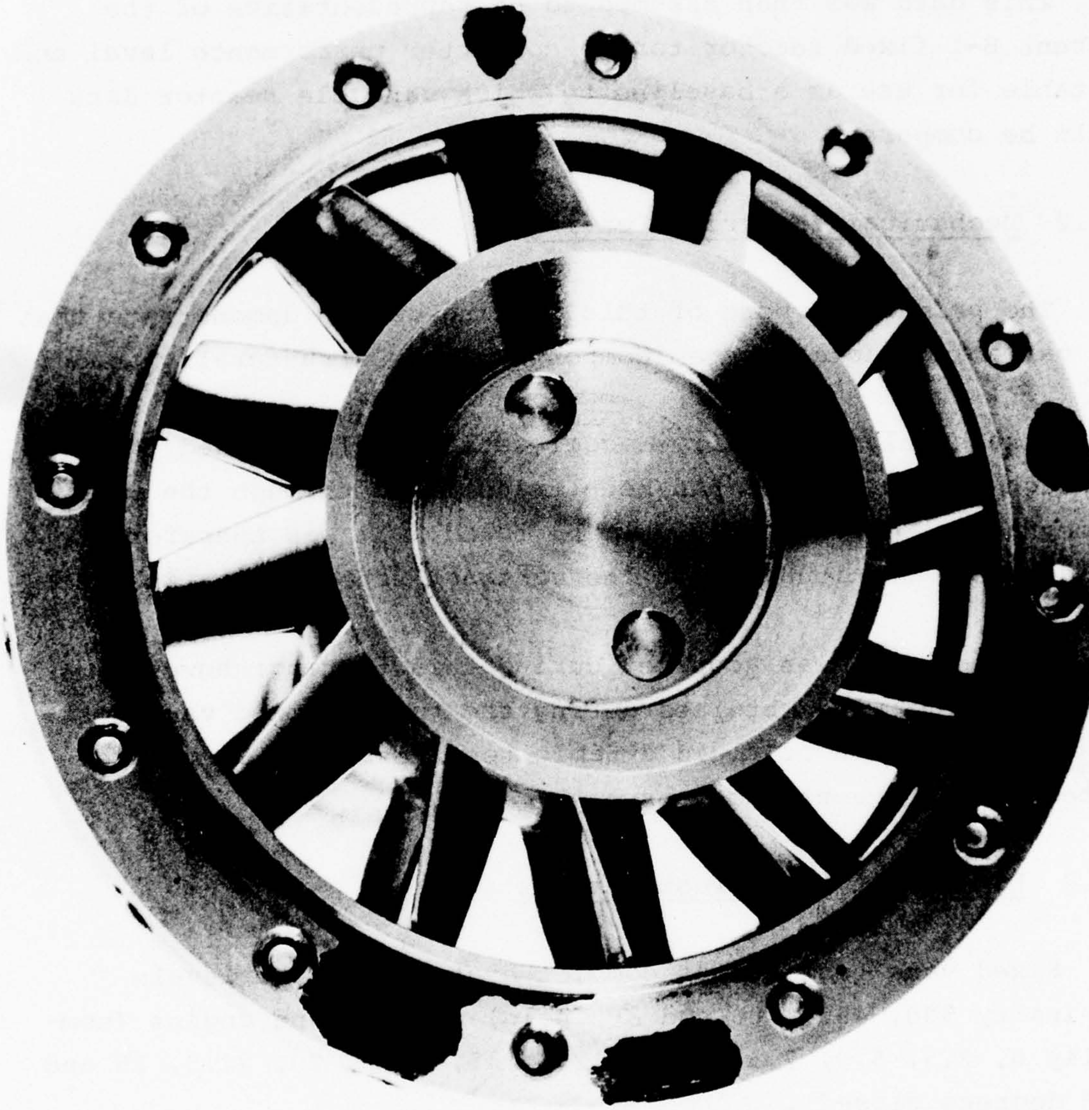


Figure 38. Variable reactor vanes fully open.

Baseline testing was accomplished at five charge pressure levels and key results are presented in Figures 39 through 43. Performance characteristics were, as expected, quite similar to previous B-1 torque converter data.

This data was then assumed to be representative of the current B-1 fixed reactor torque converter performance level and suitable for use as a baseline to which variable reactor data could be compared.

3.5.2 Mechanical Integrity Testing

The primary purpose of this testing was to demonstrate that the variable reactor system components were structurally sound.

Disassembly after three acceleration cycles showed that, although 197 horsepower had been transmitted through the unit, no mechanical discrepancy could be found. It was therefore decided that continuation of the contract schedule was in order.

Limited data was acquired during this testing; however, identical data were obtained during the formal fixed vane testing and discussion of fluid dynamic test results will be presented in subsequent sections.

3.5.3 Fixed Vane Angle Test Results

Fixed vane testing was completed at 4 pressure levels (nominally 500, 450, 400 and 300 psig) and 12 vane angles (nominally 0, 2.5, 5.0, 7.5, 10.0, 12.5, 15, 17.5, 20, 22.5, 25 and 27.5 degrees closed).

Results are presented in Appendix A (Figures A-1 through A-20). Baseline data is superimposed for comparison. Representative data at 450 psia are also presented in Figures 44 through 48.

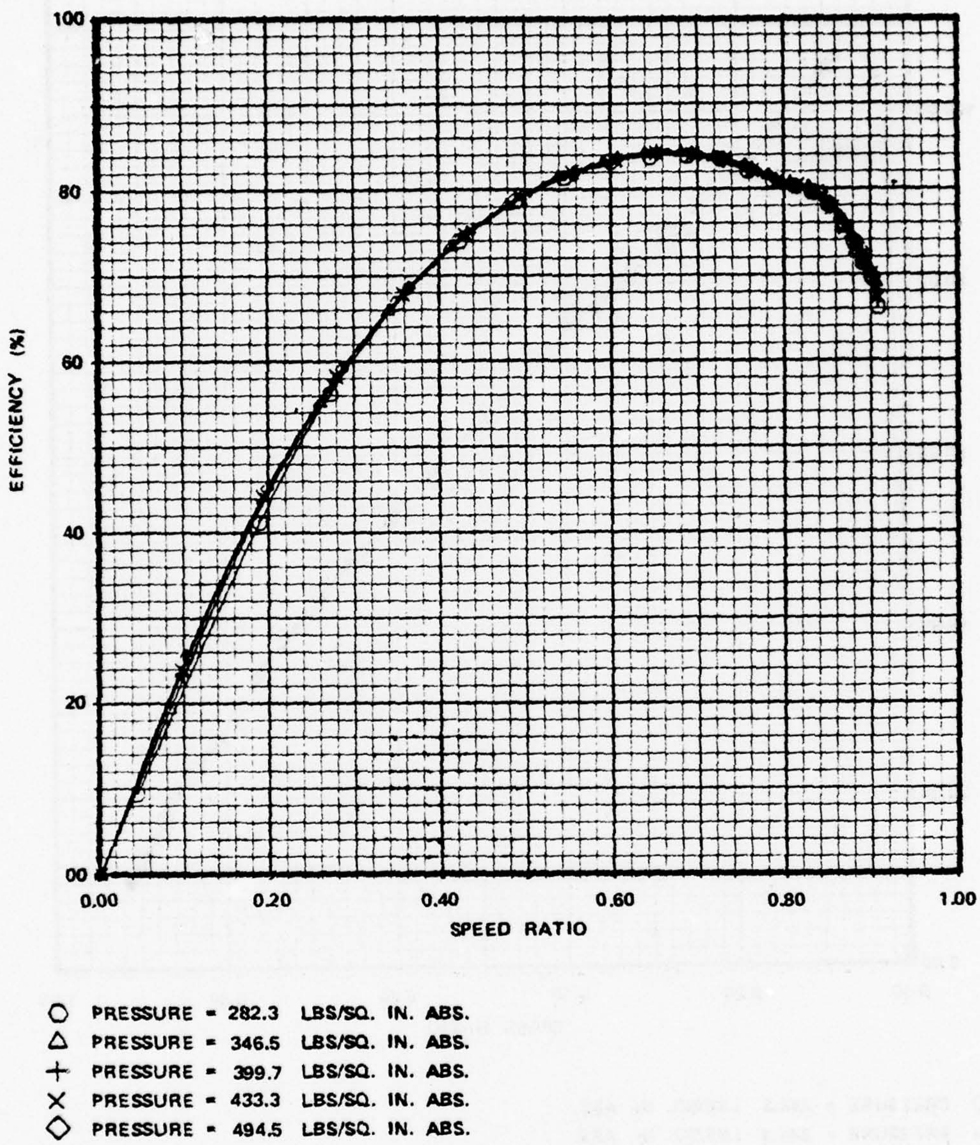


Figure 39. Torque converter baseline test.

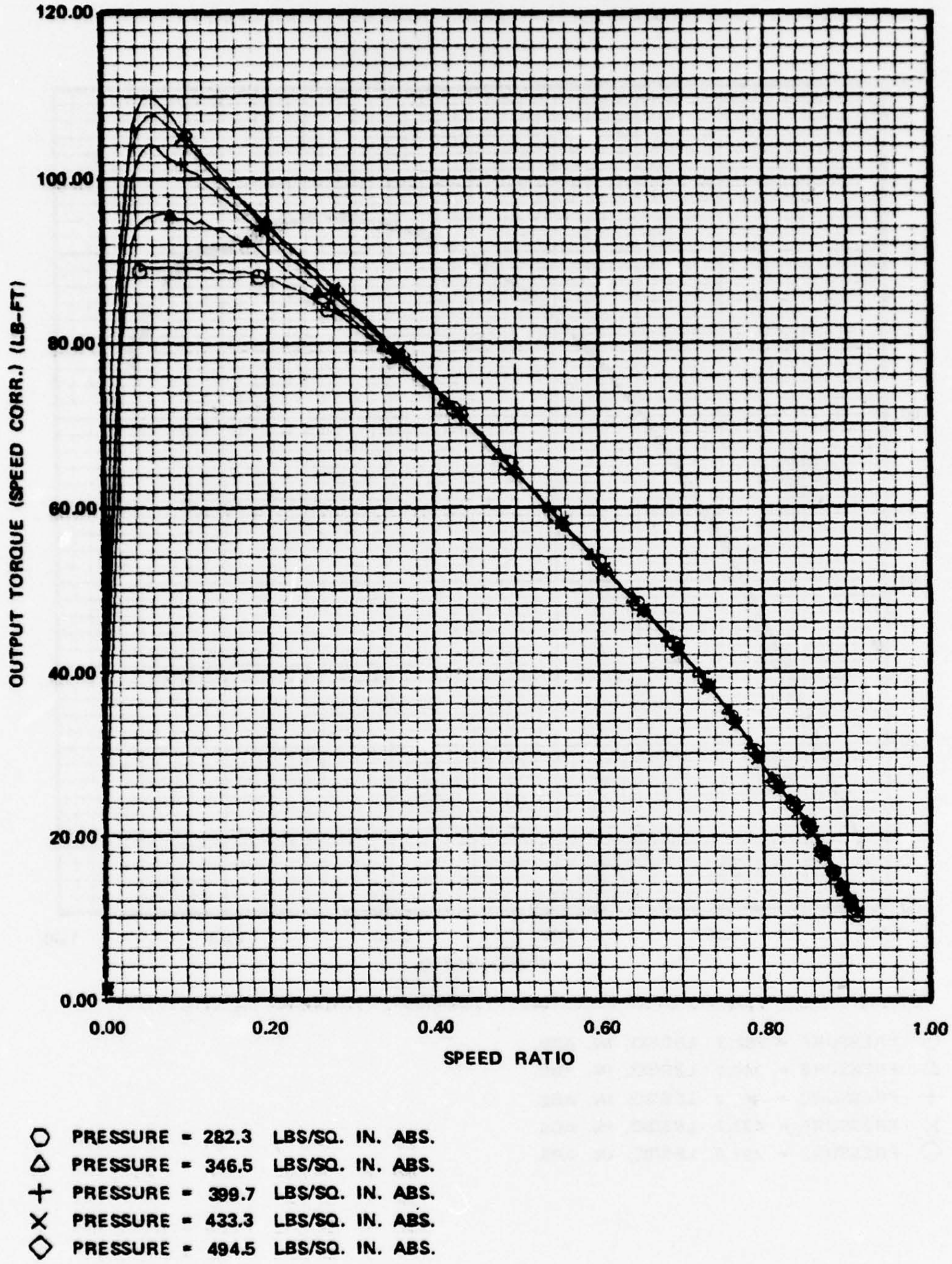


Figure 40. Torque converter baseline test.

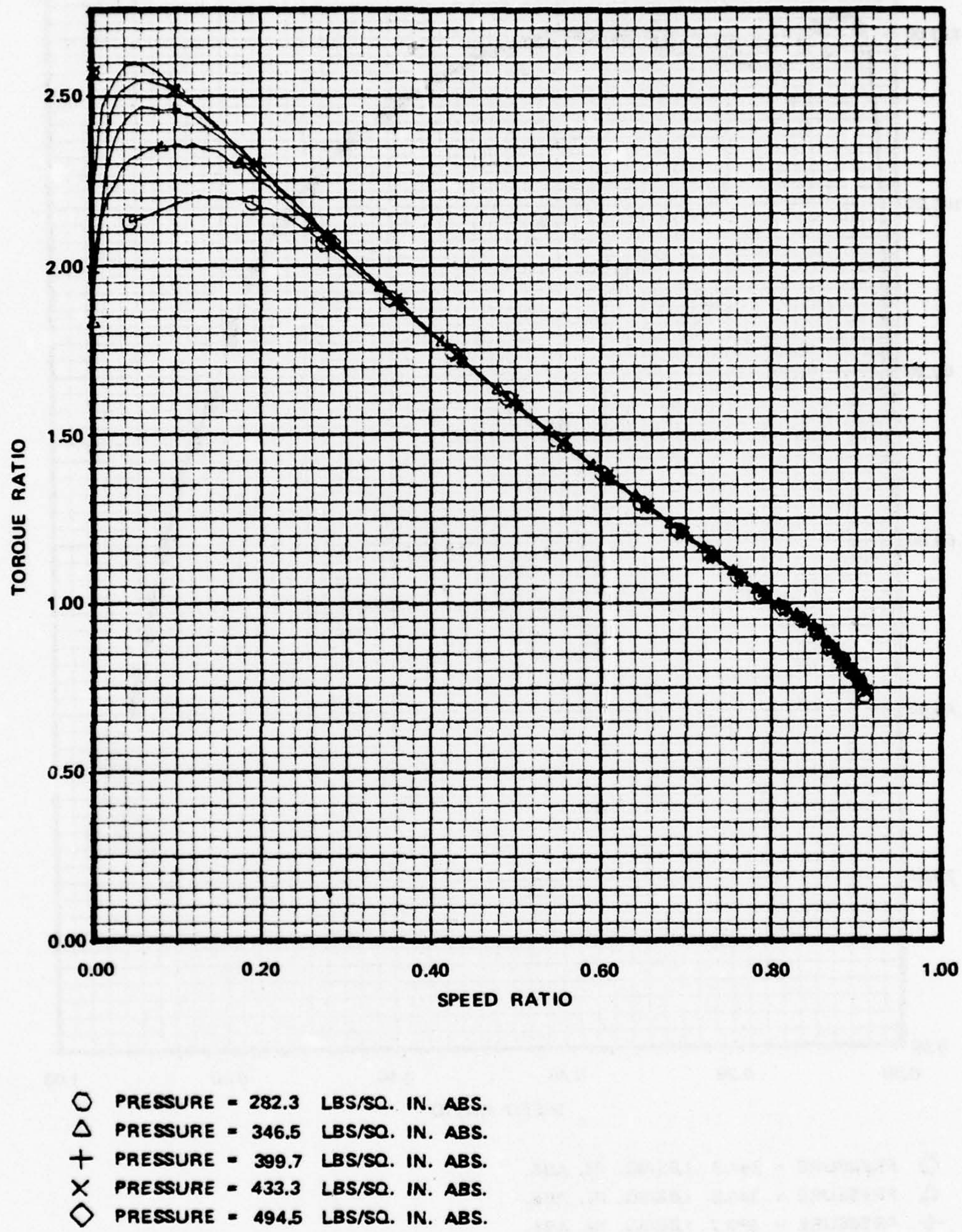


Figure 41. Torque converter baseline test.

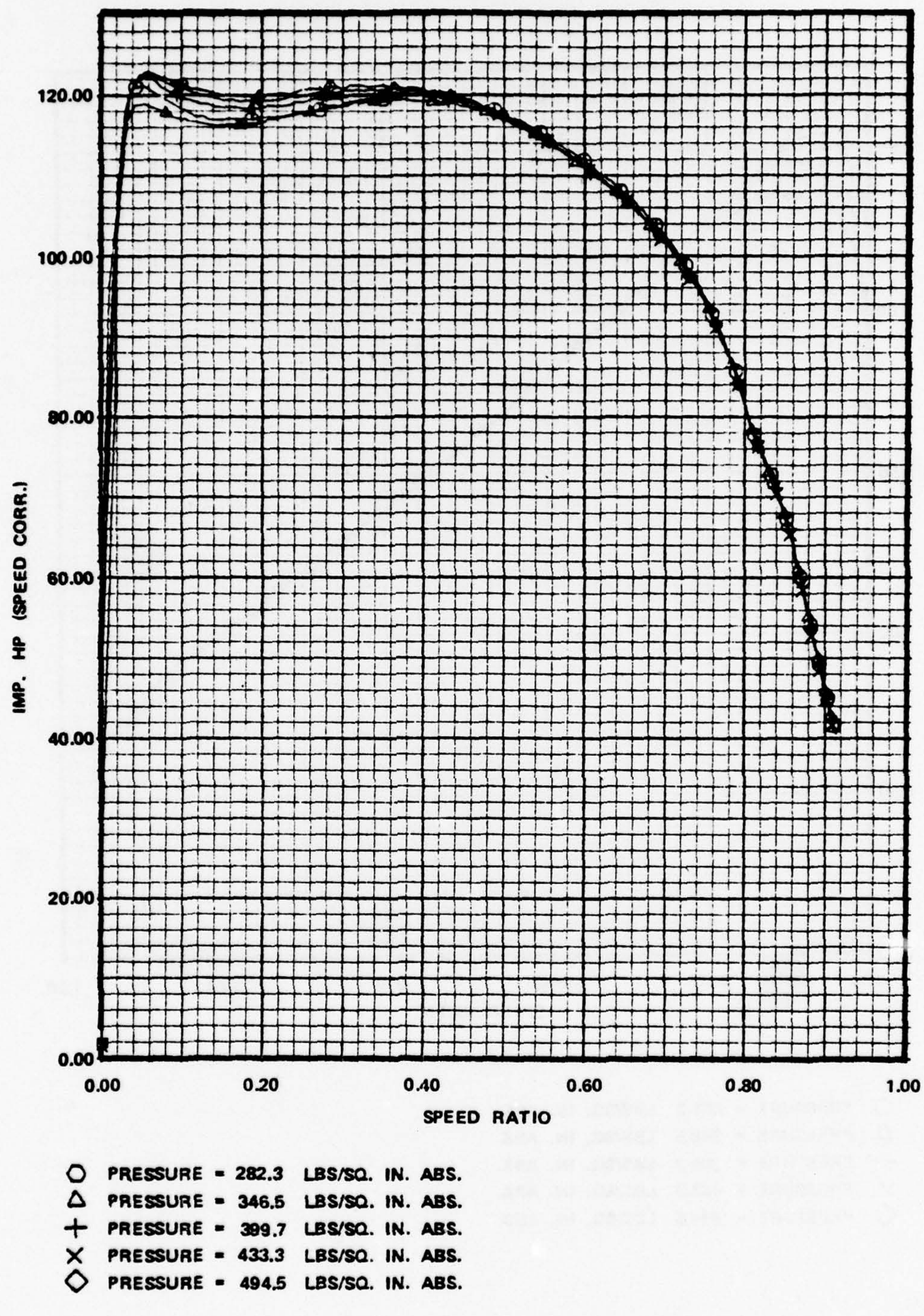


Figure 42. Torque converter baseline test.

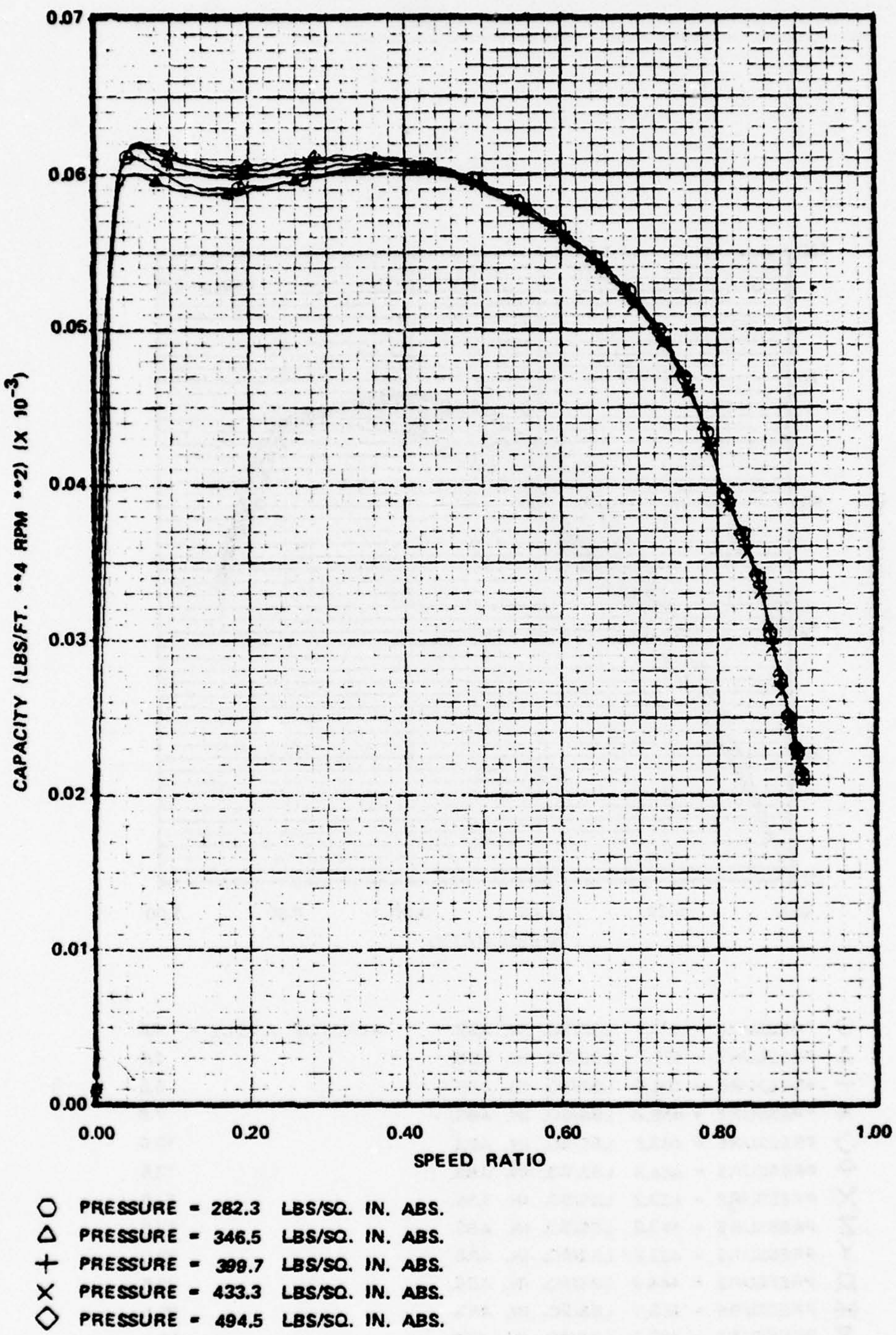


Figure 43. B-1 torque converter baseline test.

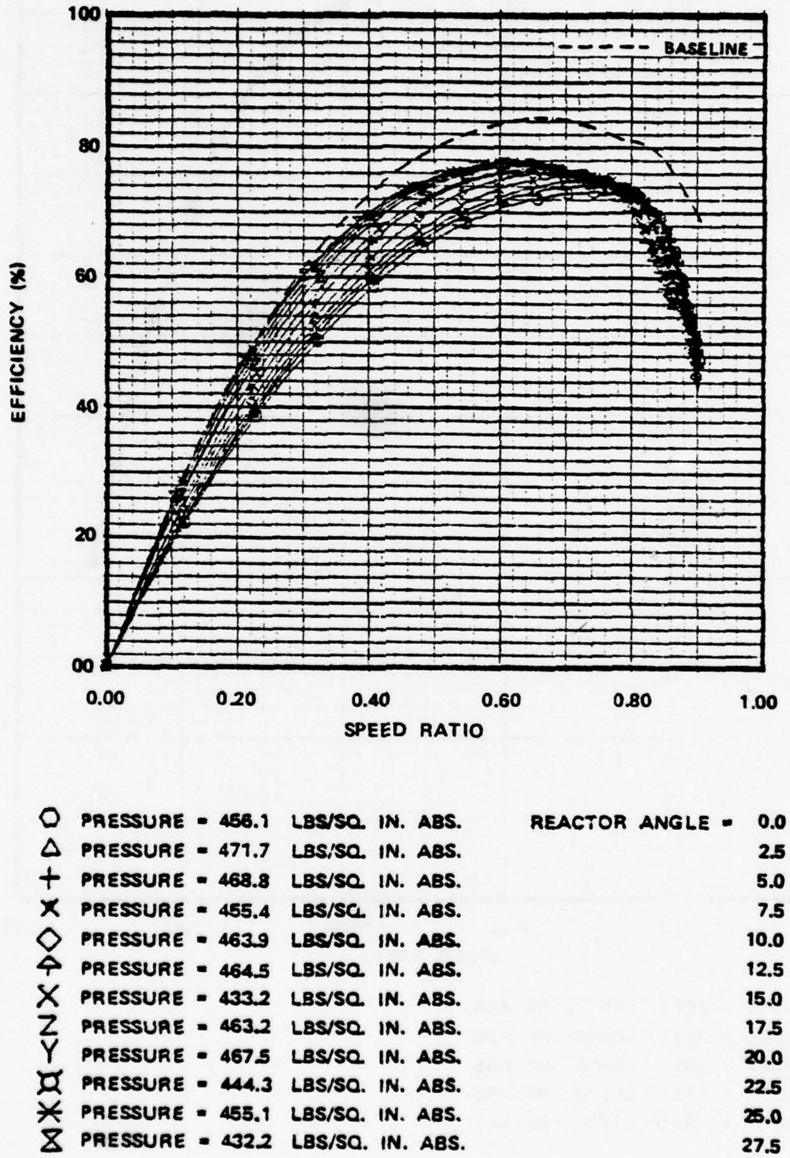
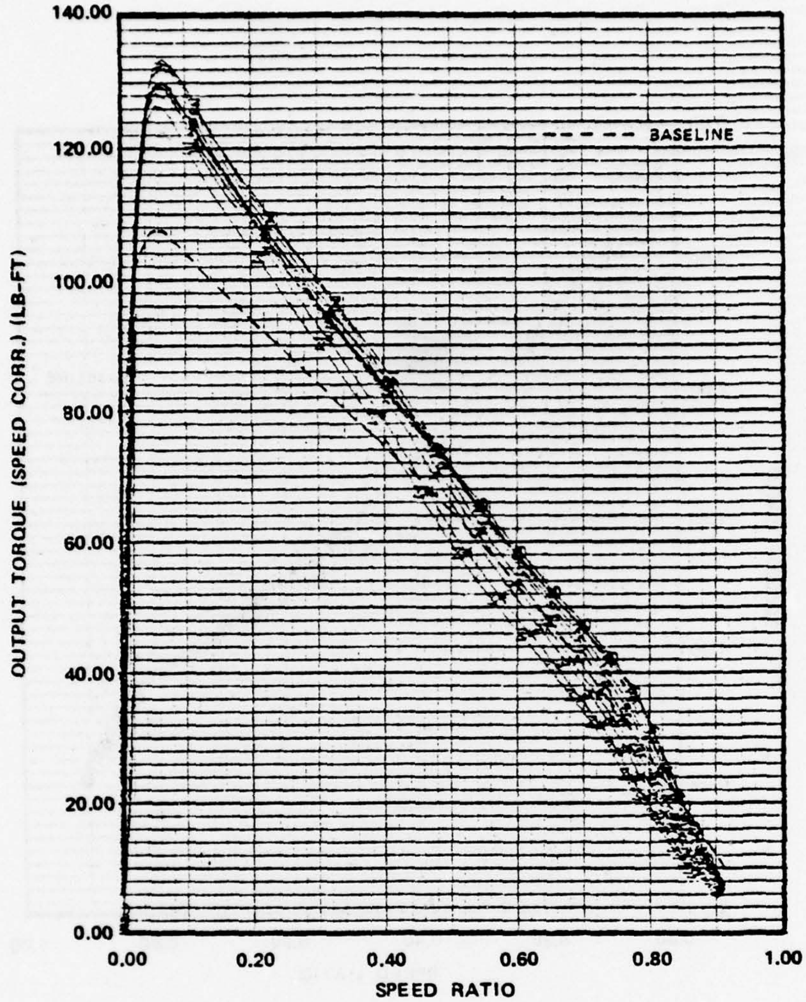
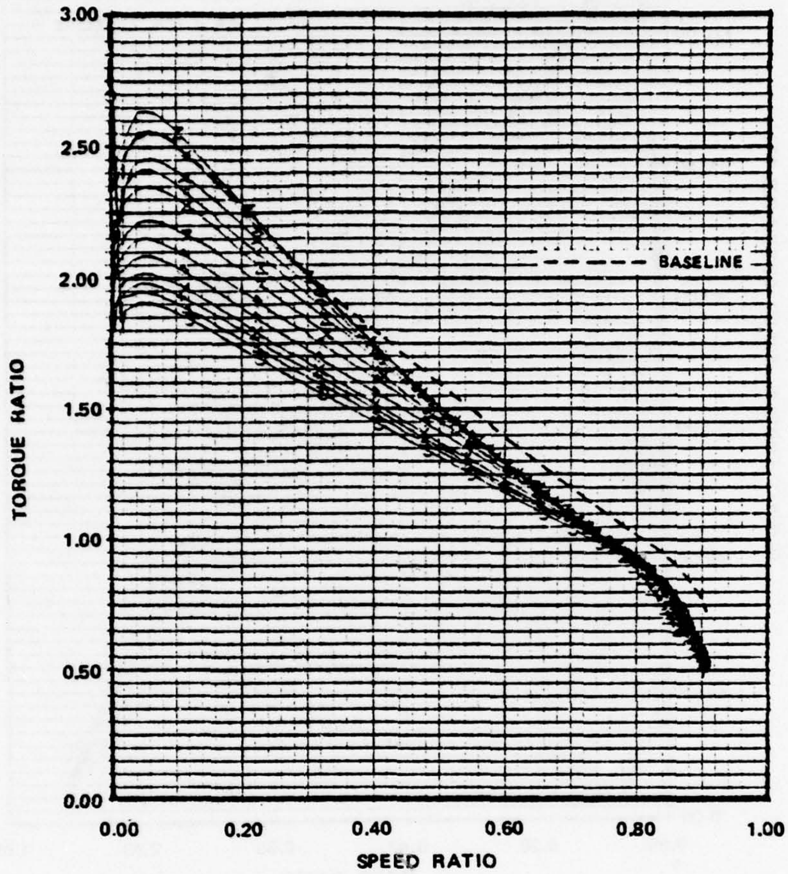


Figure 44. Fixed vane angle test--efficiency @ 450 psig.



○	PRESSURE = 456.1 LBS/SQ. IN. ABS.	REACTOR ANGLE = 0.0
△	PRESSURE = 471.7 LBS/SQ. IN. ABS.	2.5
+	PRESSURE = 468.8 LBS/SQ. IN. ABS.	5.0
✕	PRESSURE = 455.4 LBS/SQ. IN. ABS.	7.5
◇	PRESSURE = 463.9 LBS/SQ. IN. ABS.	10.0
	PRESSURE = 464.5 LBS/SQ. IN. ABS.	12.5
X	PRESSURE = 433.2 LBS/SQ. IN. ABS.	15.0
Z	PRESSURE = 463.2 LBS/SQ. IN. ABS.	17.5
Y	PRESSURE = 467.5 LBS/SQ. IN. ABS.	20.0
⌑	PRESSURE = 444.3 LBS/SQ. IN. ABS.	22.5
✳	PRESSURE = 455.1 LBS/SQ. IN. ABS.	25.0
⧖	PRESSURE = 432.2 LBS/SQ. IN. ABS.	27.5

Figure 45. Fixed vane angle test--output torque @ 450 psig.



○ PRESSURE = 456.1 LBS/SQ. IN. ABS. REACTOR ANGLE = 0.0
△ PRESSURE = 471.7 LBS/SQ. IN. ABS. 2.5
+ PRESSURE = 468.8 LBS/SQ. IN. ABS. 5.0
✕ PRESSURE = 455.4 LBS/SQ. IN. ABS. 7.5
◇ PRESSURE = 463.9 LBS/SQ. IN. ABS. 10.0
↑ PRESSURE = 464.5 LBS/SQ. IN. ABS. 12.5
X PRESSURE = 433.2 LBS/SQ. IN. ABS. 15.0
Z PRESSURE = 463.2 LBS/SQ. IN. ABS. 17.5
Y PRESSURE = 467.5 LBS/SQ. IN. ABS. 20.0
¤ PRESSURE = 444.3 LBS/SQ. IN. ABS. 22.5
✱ PRESSURE = 455.1 LBS/SQ. IN. ABS. 25.0
⧖ PRESSURE = 432.2 LBS/SQ. IN. ABS. 27.5

Figure 46. Fixed vane angle test--torque ratio @ 450 psig.

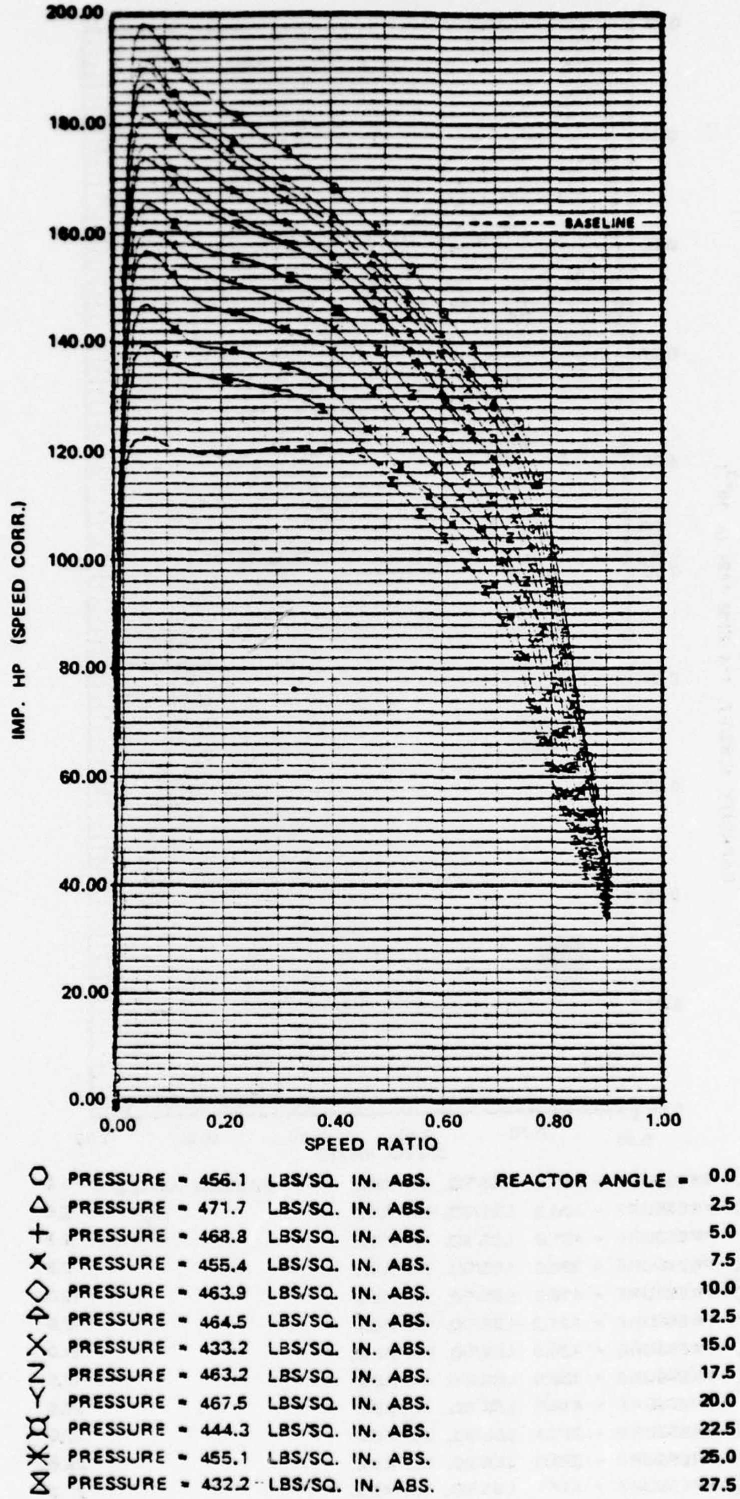


Figure 47. Fixed vane angle test--impeller hp @ 450 psig.

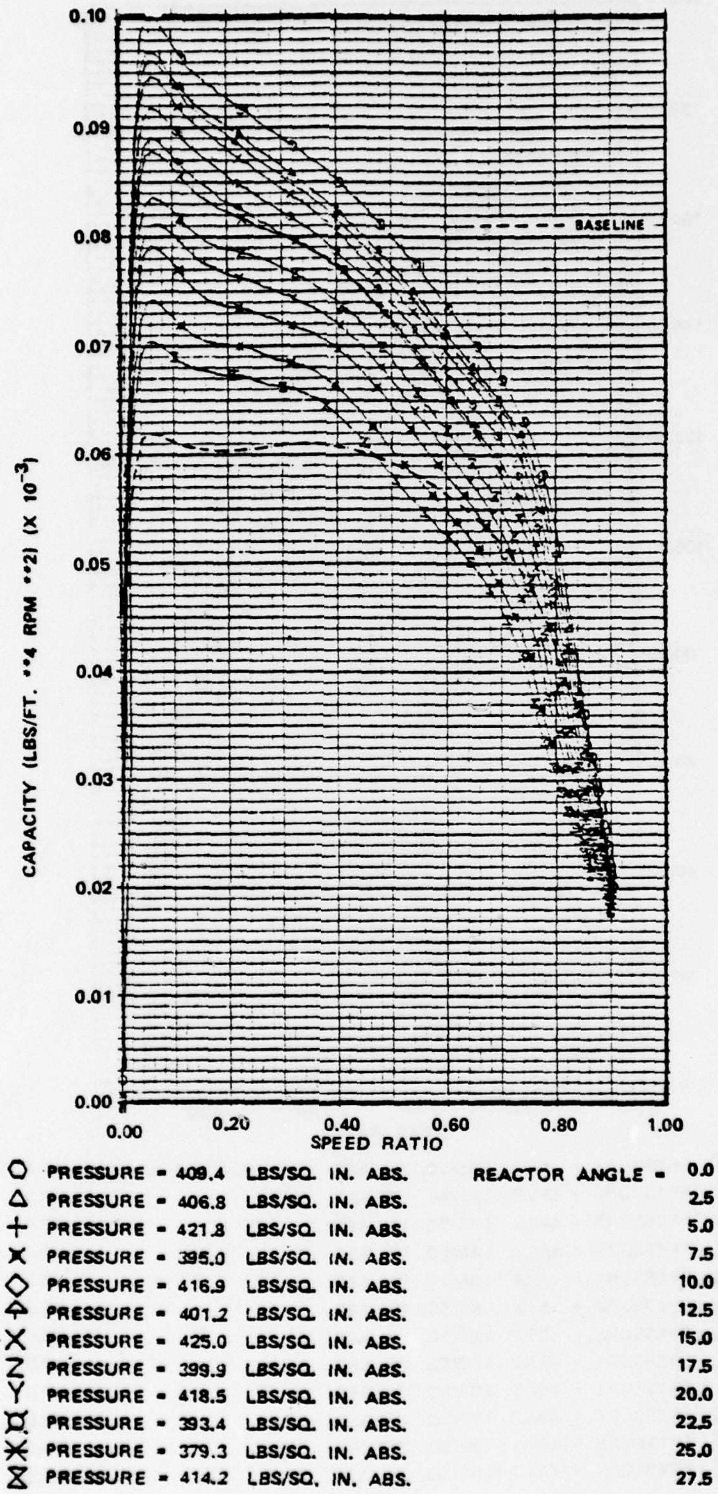


Figure 48. Fixed vane angle test--capacity @ 450 psig.

General observations from this data are:

(a) A marked difference in performance characteristics is noted. At the nominal reactor setting (Figure 47), the peak absorbed horsepower is seen to have increased from 120 hp to more than 190 hp. In addition, the horsepower variation with increasing speed ratio is markedly different, particularly at the lower speed ratios where hp decreases rapidly rather than remaining constant with speed ratio.

(b) Output torque characteristics are compared in Figure 45. While the general trends are similar, the output torque level has increased significantly with the variable reactor, although not as much as the input hp. This is reflected in the generally lower efficiency and torque ratios indicated in Figures 44 and 46. This was not the case for the baseline.

(c) Efficiencies generally improve as the reactor is closed although peak efficiency stops rising at about the 20° closed setting.

(d) Even when the variable reactor is closed to mechanical limits (reactor vanes touch each other at one radial position) of 27.5°, the maximum horsepower absorbed by the impeller is higher (approximately 135 vs 120 hp) than for the baseline configuration with the reactor at nominal setting (0° closed).

In summary, the B-1 torque converter performance with the variable reactor installed is quite different from what was anticipated. In fact, it is similar to what could be expected with a reactor in an extreme opened position.

The following rationale is offered to explain the differences in performance between the baseline and variable reactor:

(a) The mechanical restraints imposed by the B-1 baseline torque converter components did not permit use of the same vane contour in the variable reactor.

(b) The final variable reactor contour has a different meanline angle distribution than the baseline design.

(c) Both reactor designs have the same exit mean blade angle (28°). This angle was held constant for up to 2/3 of the blade length in the fixed reactor, while in the variable reactor, the 28° angle occurs only near the trailing edge. (See Figure 18.)

(d) The net result of Items (a) through (c) may be that the variable reactor cascade has lower flow turning capability; i.e., it has a higher deviation than the more conventional fixed design. Thus, even though both designs have the same exit blade angle, the mean exit fluid angle could be significantly larger for the variable reactor resulting in the observed higher capacity.

If the above hypothesis is correct, most of the observed data can be explained as follows:

- At nominal setting, with the variable reactor exit flow angle deviating significantly from the blade exit angle, the effect is the same as if the original fixed reactor exit angle were opened by several degrees, i.e., more horsepower is absorbed by the impeller but overall efficiency is reduced because of the incidence losses at the impeller and turbine leading edges due to mismatching with respect to the original design condition.

- As the variable reactor is closed down, the exit flow angle approaches the exit flow angle of the original reactor, finally achieving it when the variable reactor is closed to its mechanical limit. At this point, the incidence angles on all components are close to those of the original reactor. However, because the variable reactor is in such an abnormal configuration, its loss is high and the overall efficiency level is lower than that of the original reactor.

- The fact that the turbine output torque is insensitive to charge pressure level with the variable reactor installed could be further indication that the turbine inlet conditions vary so greatly from normal that cavitation effects are not affected by increased charge pressure (up to the limits of the test pumps).

3.5.4 Modulated Vane Test Results

Two different modes of modulation were tested. In the first mode, the reactor vanes were moved from nominal setting to 27.5° closed during flywheel acceleration. In the second mode the vanes were opened from 27.5° to the nominal position. Both modes were tested with modulating times of 15 and 20 secs.

Results are presented in Appendix A (Figures A-21 through A-32). Reactor position as a function of speed ratio is also included in this data.

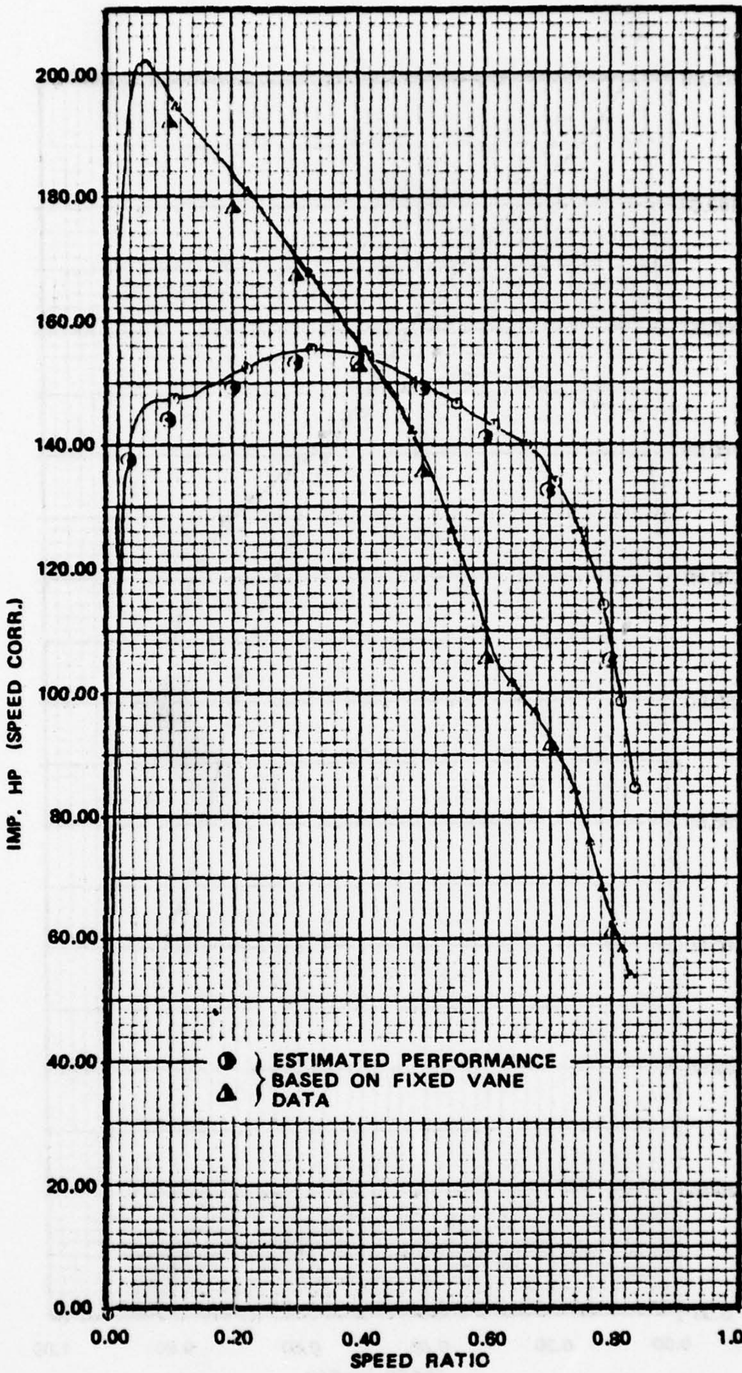
This testing demonstrates the feasibility and flexibility of operation with a variable geometry torque converter. Note that dramatic changes in torque converter characteristics can be obtained. This is particularly evident in the impeller hp versus speed ratio curves (Figures 49 and 50). Therefore, the goal of controlling the power match has been demonstrated.

On Figure 49 the estimated impeller hp with modulating vanes has been predicted using the fixed vane data from Paragraph 3.5.3. The excellent agreement with the modulating data indicates that, with judicious use of fixed reactor data and proper scheduling of reactor vane angle with speed ratio, a wide variety of horsepower schedules can be maintained.

3.5.5 Over-Open Fixed Vane Test Results

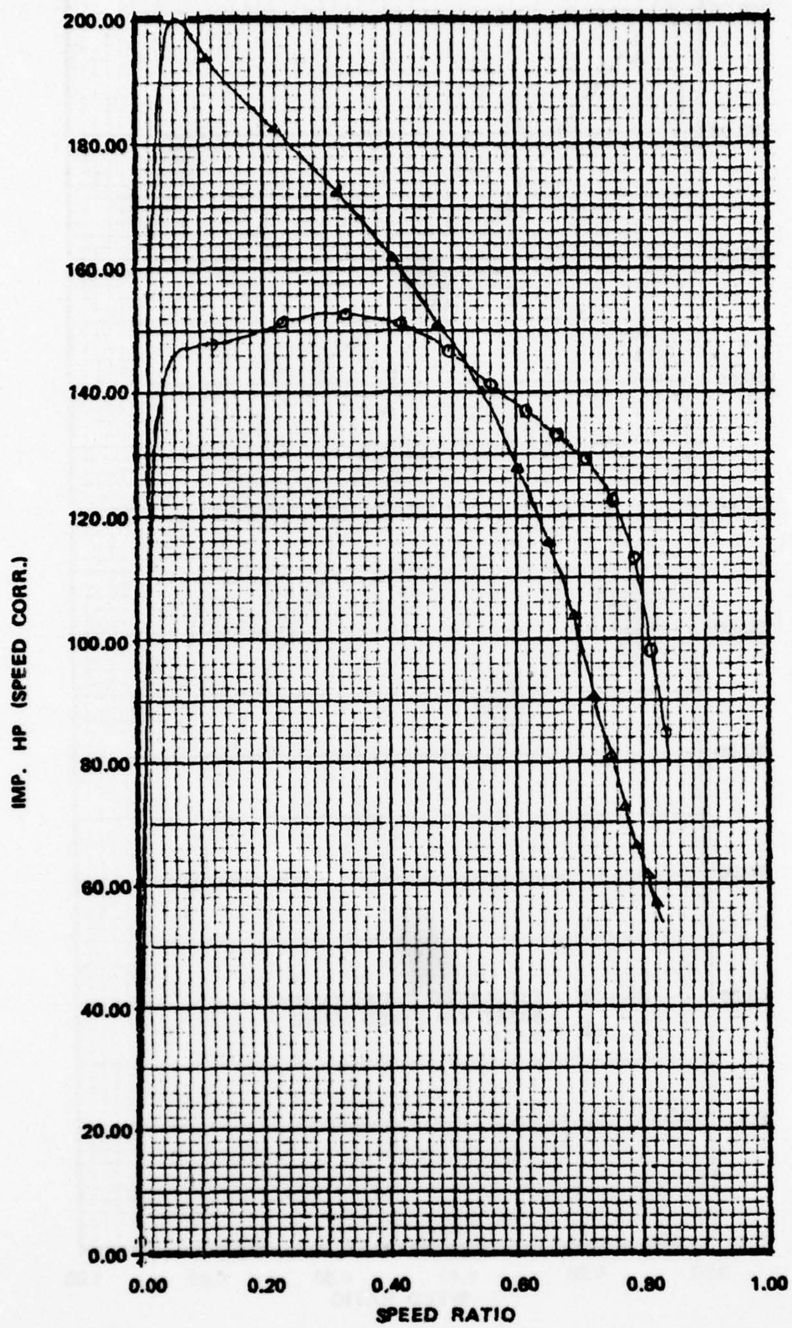
Data was taken at 4 vane angles opened beyond the nominal position (3, 5, 8 and 16 degrees). Each angle was tested at 300 and 450 psi charge pressures.

Data from these tests is presented in Appendix A (Figures A-33 through A-42). This data continues the trend indicated by



○ PRESSURE = 456.3 LBS/SQ. IN. ABS. REACTOR ANGLE = CLOSED-TO-OPEN
△ PRESSURE = 465.8 LBS/SQ. IN. ABS. OPEN-TO-CLOSED

Figure 49. Modulated vane test (15 sec), impeller hp.



○ PRESSURE = 453.0 LBS/SQ. IN. ABS. REACTOR ANGLE = CLOSED-TO-OPEN
△ PRESSURE = 463.5 LBS/SQ. IN. ABS. OPEN-TO-CLOSED

Figure 50. Modulated vane test (20 sec), impeller hp.

the previous data, i.e., opening the vane increases absorbed impeller hp (Figure 51) but efficiency decreases by about the same amount (Figure 52) so turbine output power remains essentially constant.

Thus, for this particular configuration, opening the reactor beyond 0° or nominal setting serves no practical purpose.

3.5.6 Test Conclusions

(a) The mechanical feasibility of using a variable reactor in a small, high-power torque converter has been successfully demonstrated.

(b) The desired program goal of adjusting torque converter power absorption over a 120 to 30 hp range in order to match typical gas turbine power characteristics has not been completely attained.

Impeller power absorption unexpectedly increased from about 120 to about 200 hp for identical exit vane angles and charge pressures when the articulated reactor vanes replaced the original fixed reactor vanes in the B-1 torque converter.

Peak absorbed impeller hp could only be reduced from 200 to 140 hp by closing the variable reactor to the mechanical limit. This reduction was less than desired.

(c) The unexpectedly different performance characteristics of the variable reactor appear to be caused by design restraints inherent in replacing a fixed vane design with a variable articulated vane that must fit in a given meridional flow path.

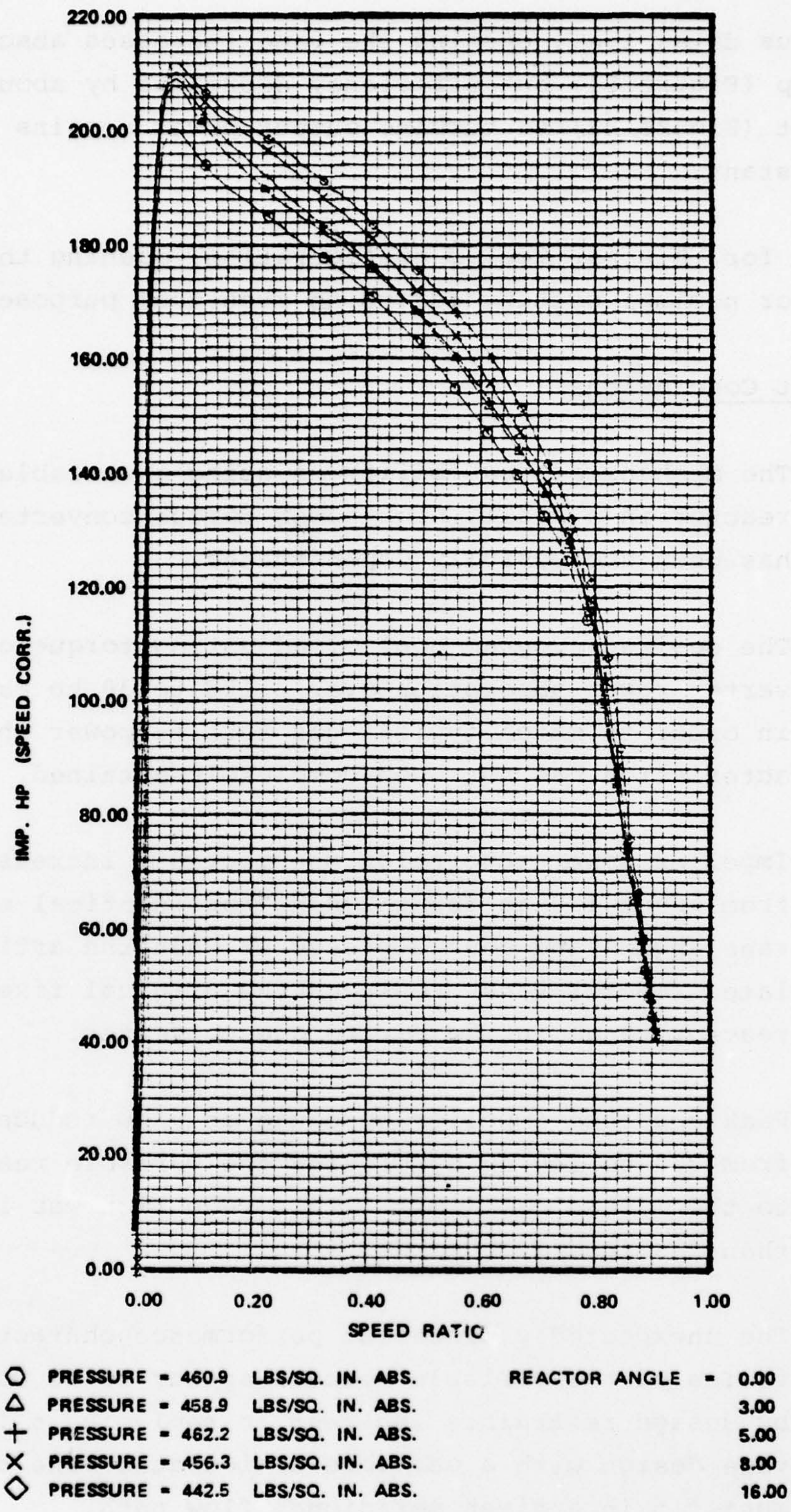
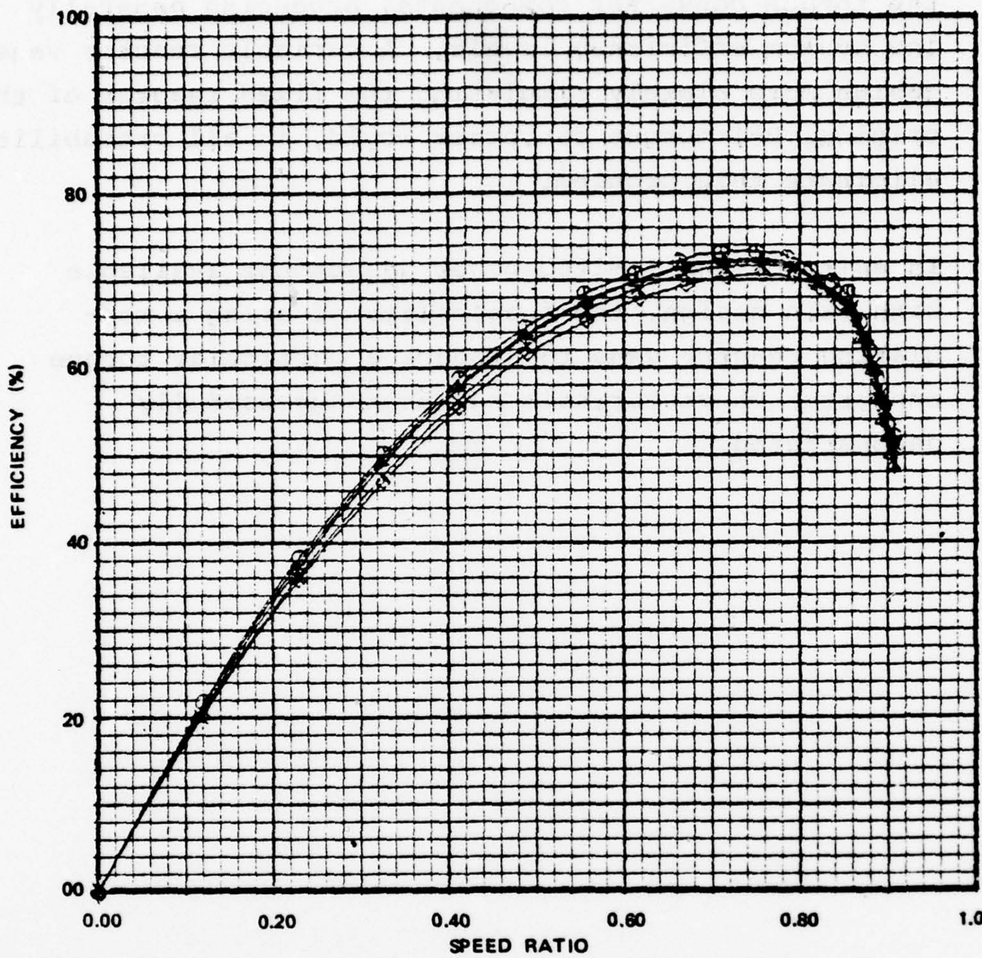


Figure 51. Over-open fixed vane test (450 psig), impeller hp.



○ PRESSURE = 460.9	LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.00
△ PRESSURE = 458.9	LBS/SQ. IN. ABS.		3.00
+ PRESSURE = 462.2	LBS/SQ. IN. ABS.		5.00
× PRESSURE = 456.3	LBS/SQ. IN. ABS.		8.00
◇ PRESSURE = 442.5	LBS/SQ. IN. ABS.		16.00

Figure 52. Over-open fixed vane test (450 psig), efficiency.

(d) Test results indicate that the specific variable reactor design used in this program allows much greater deviation between exit flow angle and reactor vane exit angle. This dramatically changes impeller inlet vector triangles and disrupts the fluid dynamic match between the torque converter components, producing generally low system efficiency levels. A variable reactor vane design more closely simulating the fixed reactor of the original B-1 torque converter would, in all probability, eliminate this problem.

(e) In spite of the limited power adjustment available with this design, the feasibility of using a modulating reactor vane to produce a particular torque converter characteristic has been successfully demonstrated.

SECTION IV

CONTROL SYSTEM

4.1 Control System Design

Following the test program, a control system was designed to be compatible with an aircraft SPS control system and provide the control functions necessary to realize the full potential of the variable geometry torque converter in an airborne APU application.

Figures 53 and 54 show a variable reactor torque converter blade angle control system controlled to transmit maximum torque during main engine cranking over the operating ambient range.

The electronic portion logic is shown to be an addition to an existing electronic control assembly (ECA) such as the B-1 SPS ECA, so component commonality would be preserved wherever possible. Sensors such as T_2, T_5, torque converter turbine and impeller speed are presently available in the current B-1 system.

Figure 55 depicts variable reactor torque converter performance, plotting variable impeller horsepower versus speed ratio. An infinite number of operating lines may be chosen from Figure 55, restricted by the APU temperature limitations, the accessory drive gearbox (ADG) torque capabilities, desired main engine acceleration characteristics, etc.

With reference to the control system of Figure 53, ambient temperature (T_2) is the input to a function generator (the function shown in Figure 56) yielding a turbine discharge limit (T_5) for a given permissible turbine inlet temperature. This signal is compared with the actual exhaust temperature. When the turbine discharge temperature exceeds the limit, an error signal (shown in Figure 57) will pass to a summing junction.

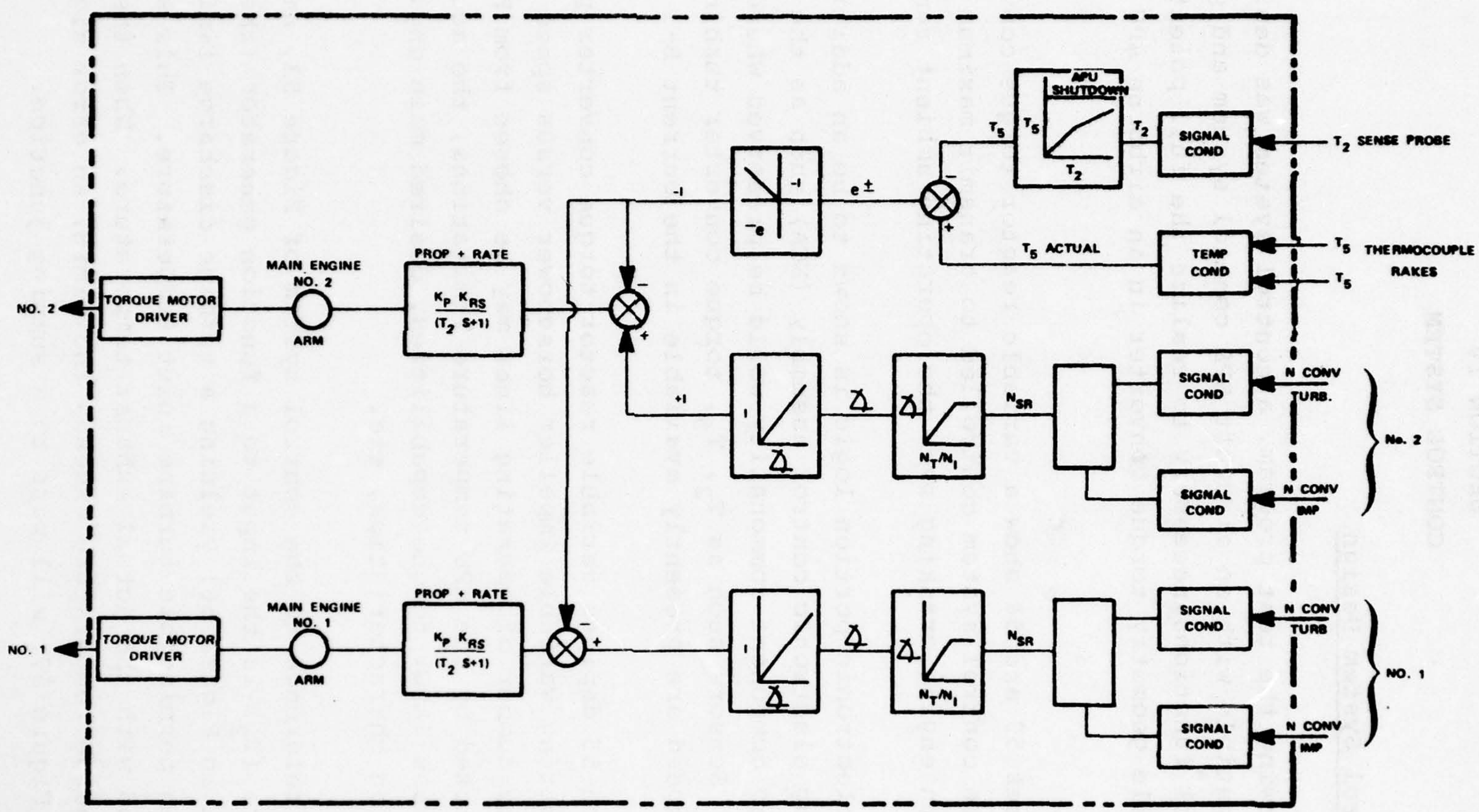


Figure 53. Blade angle control system -- electronic portion.

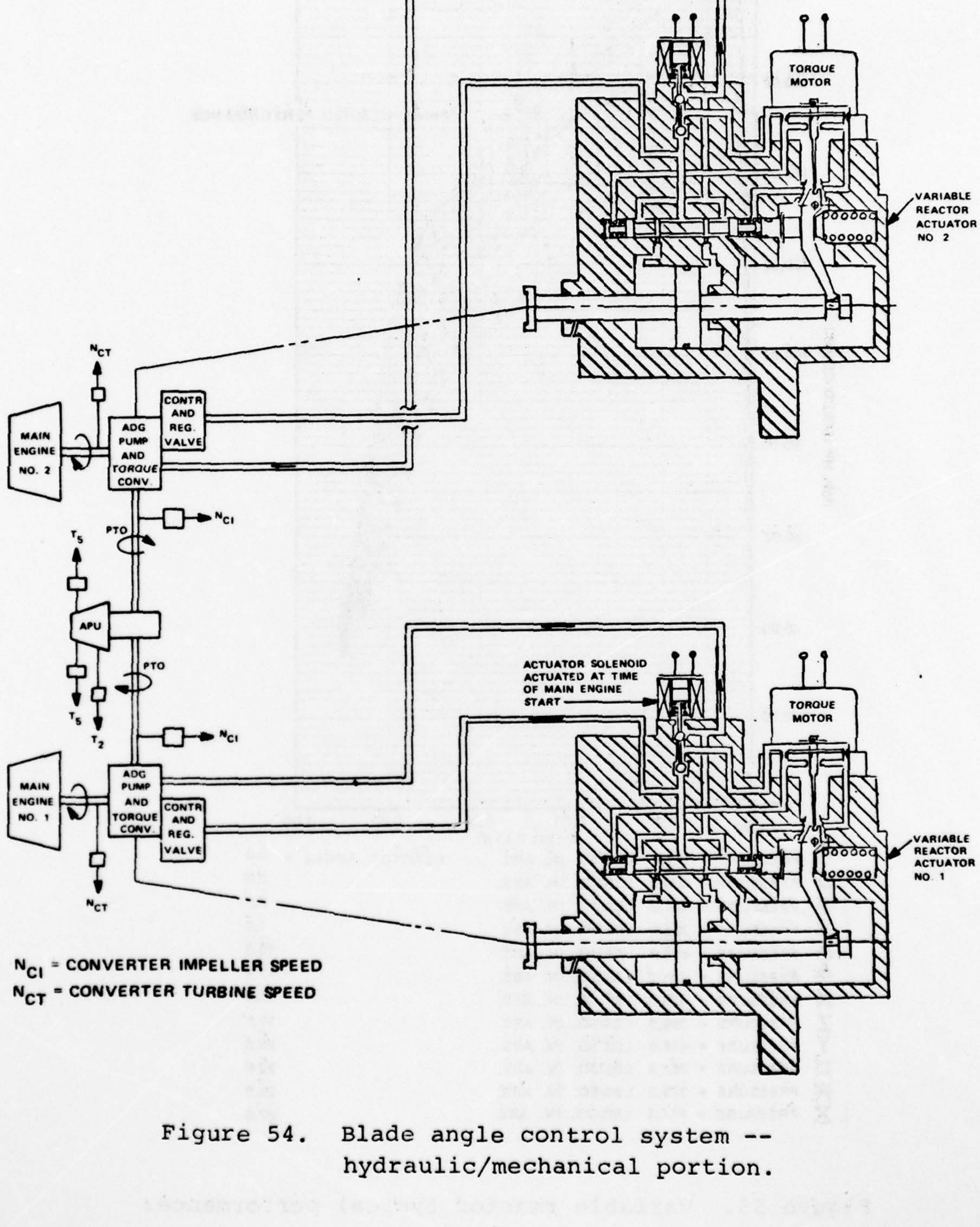


Figure 54. Blade angle control system -- hydraulic/mechanical portion.

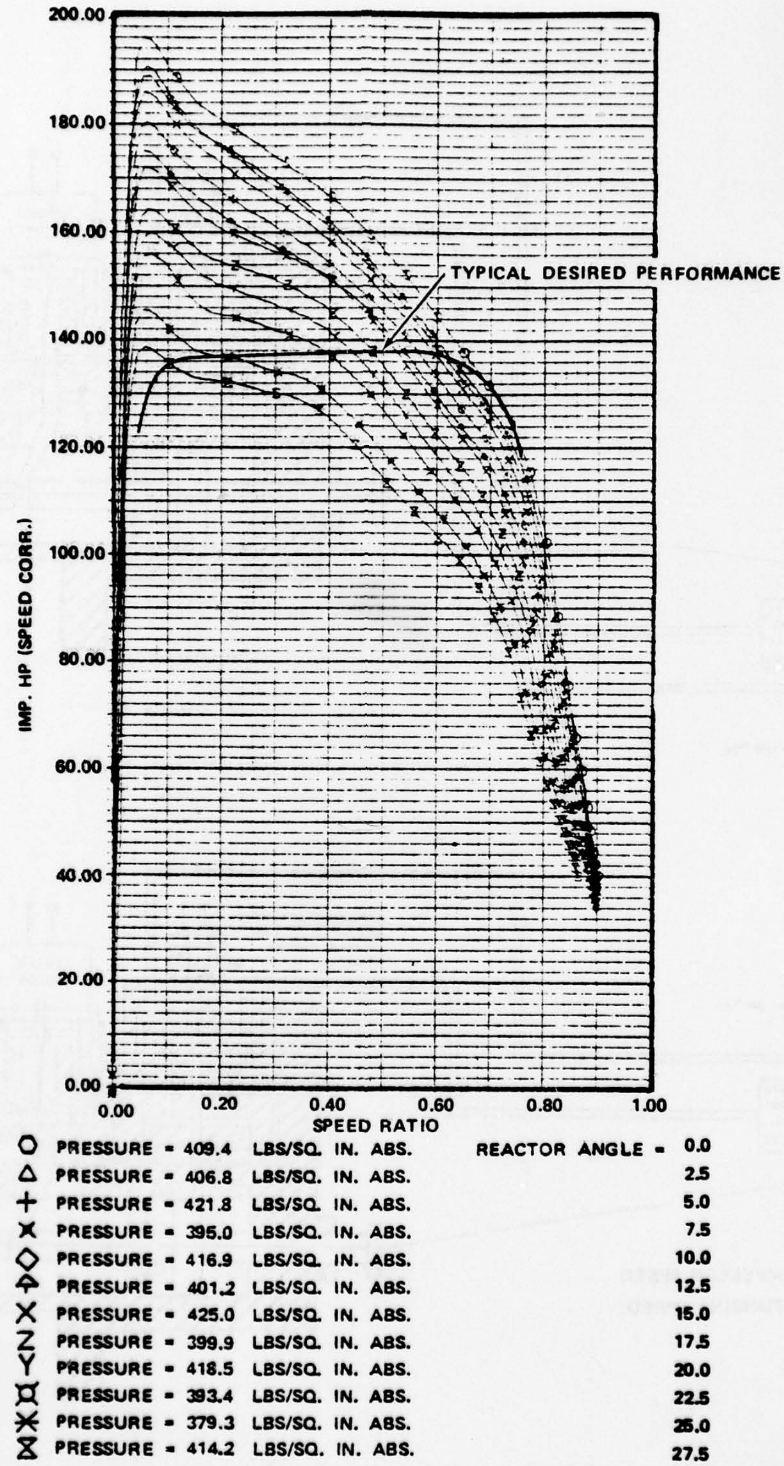


Figure 55. Variable reactor typical performance.

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VARIABLE GEOMETRY TORQUE CONVERTER.(U)
APR 78 K W BENN, G L PERRONE F33615-76-C-2013
UNCLASSIFIED 31-2775A AFAPL-TR-78-18 NL

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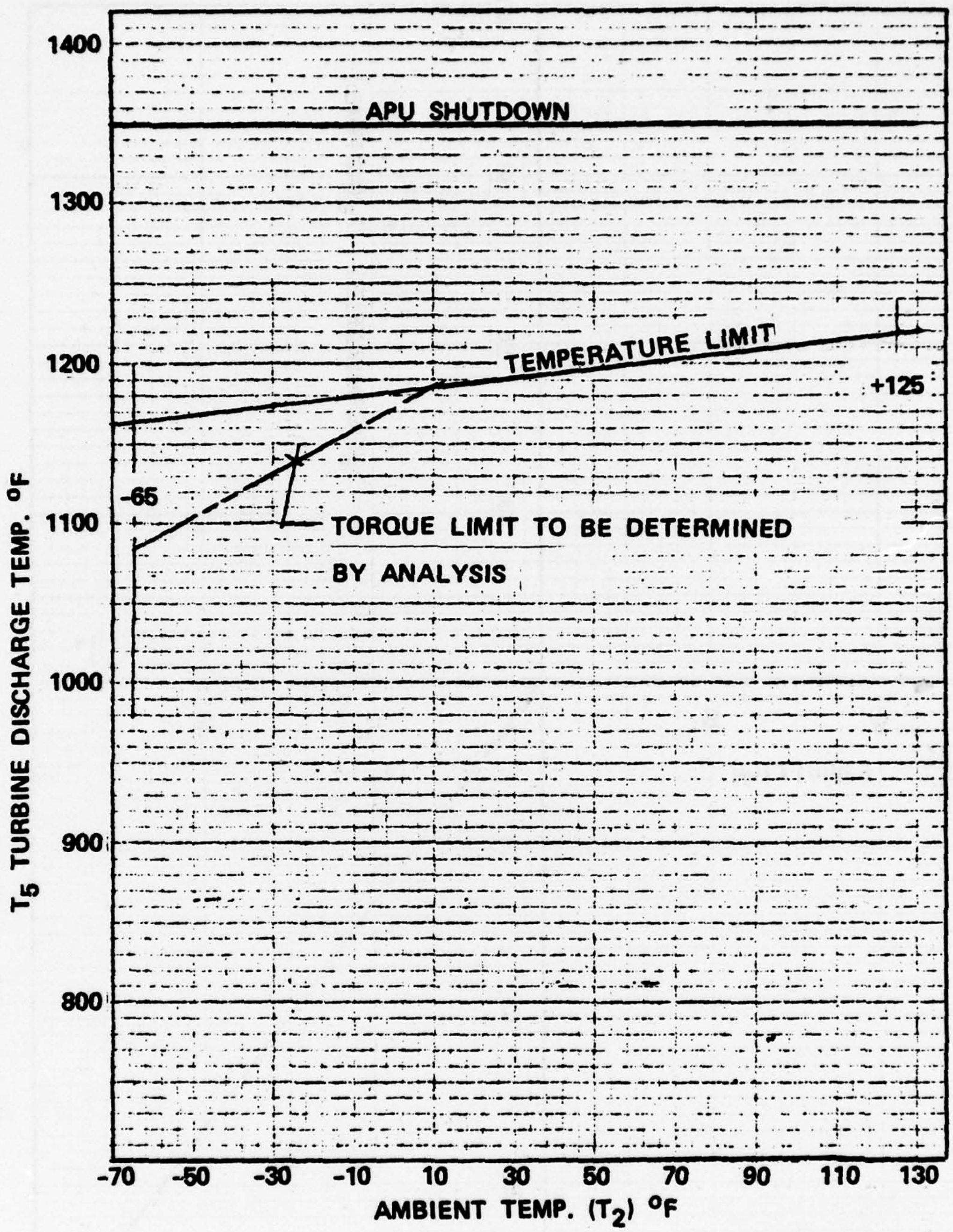


Figure [illegible]. Temperature set point for the converter control EGT (T_5).

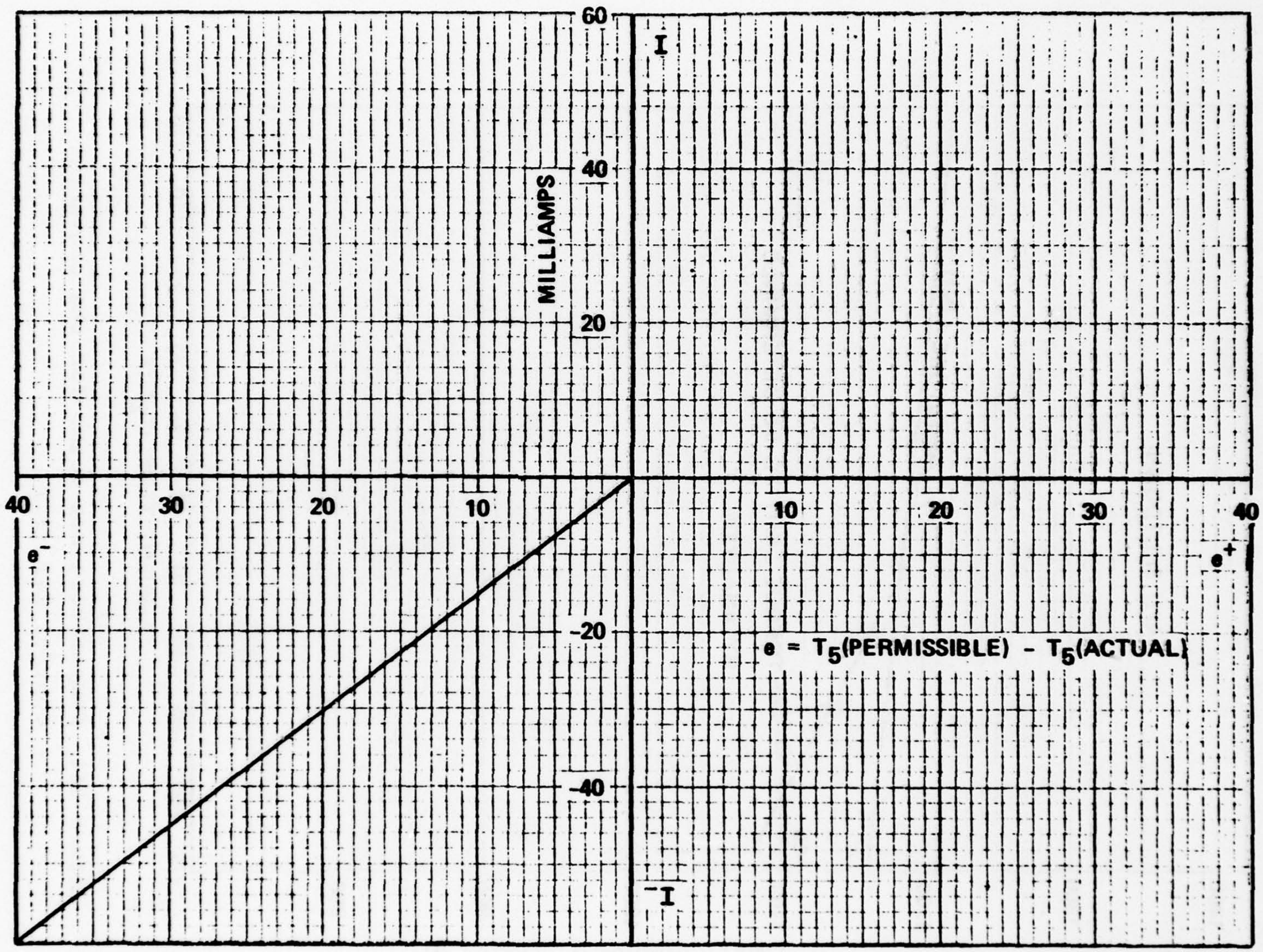


Figure 57. Milliamperes versus temperature error.

Converter impeller and turbine speed result in a speed ratio (N_{SR}). With N_{SR} as input, a function generator (the function shown in Figure 58) provides a reactor angle to meet the desired power as depicted in Figure 55.

If the requested reactor angle overloads the APU in terms of turbine temperature, the reactor angle will be reduced to ride the APU exhaust gas temperature limit as the main engine is accelerated with the maximum possible torque. The control mode will be proportional plus rate. Sudden temperature changes in excess of the limit, will immediately result in reactor angle reduction in spite of thermocouple lag prior to going on proportional control. Figure 56 can be modified as shown, to limit torque transmitted at lower ambient temperatures.

The reactor actuator is a proportional hydraulic power servo with input amplified in two stages. Input to the actuator torque motor is shown in Figure 59. Regulated oil pressure is supplied to the actuator from the ADG control. When the electronics output is armed to start a main engine, the appropriate torque converter actuator solenoid is energized, admitting regulated oil pressure to the torque motor servo circuit.

The torque motor circuit is nulled when the armature is in mid-position. Energizing the torque motor causes the torque motor ouput arm to deflect, changing the pressure balance on the pilot valve, which moves the valve in a direction to uncover the piston supply and drain ports as required to move the piston in the desired direction. Movements of the piston are fed back to the high gain torque motor circuit through action of the feedback lever, producing an accurate system under load.

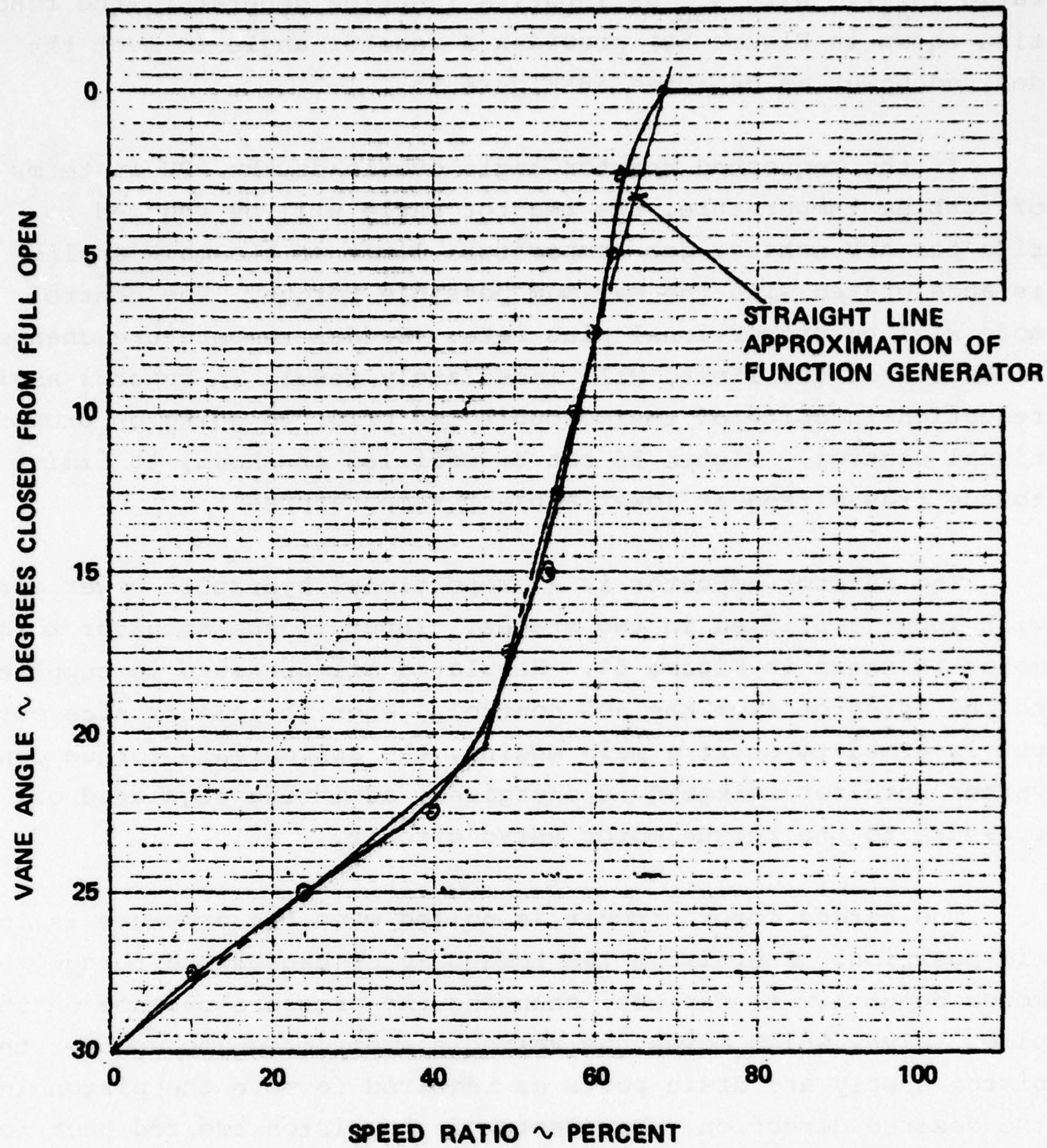


Figure 58. Converter vane angle versus speed ratio $\frac{N_T}{N_I}$

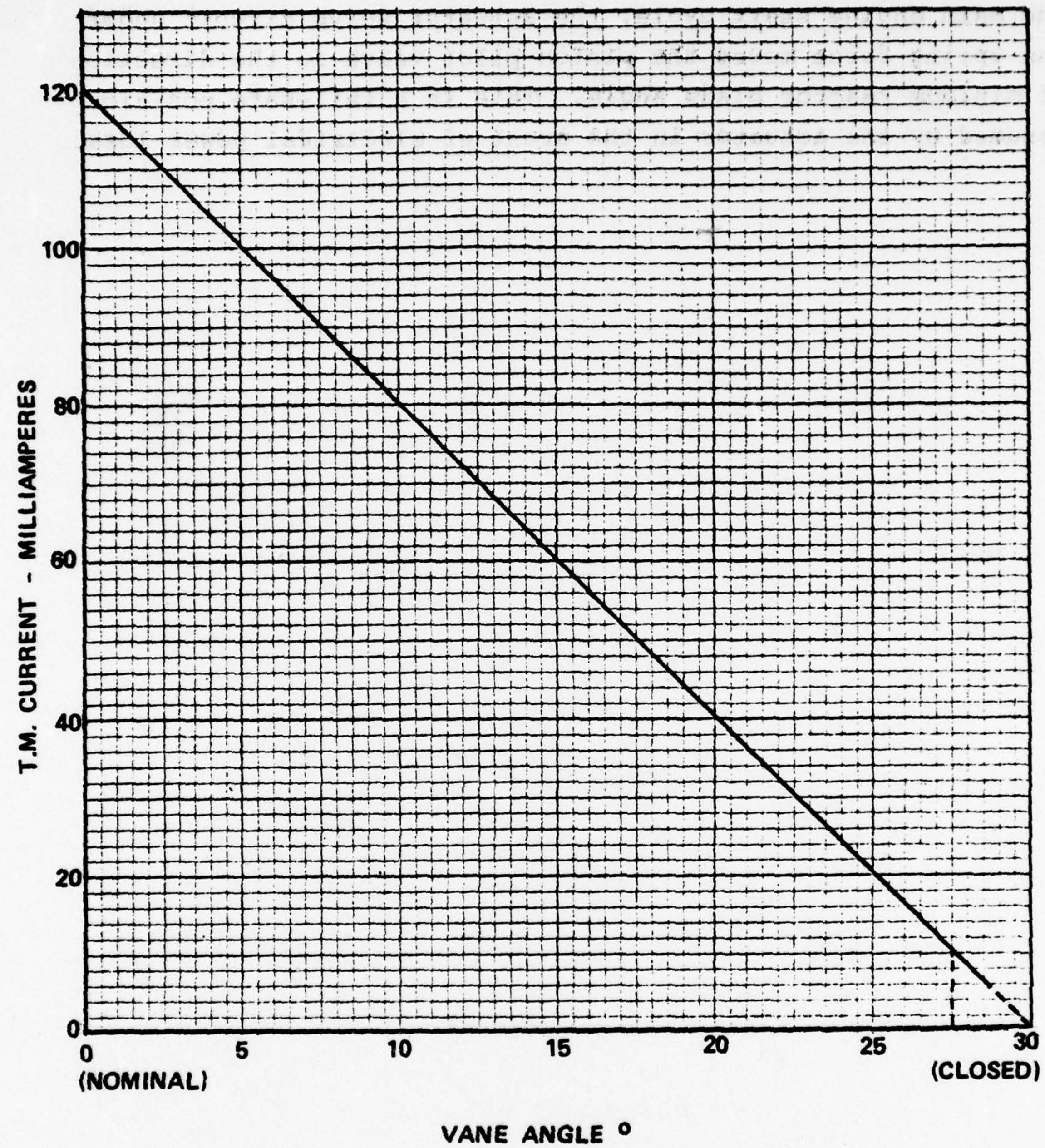


Figure 59. Torque motor current versus vane angle.

When the actuator solenoid is de-energized at completion of the main engine start cycle, the actuator servo circuit under the spring force moves the piston pilot valve in the direction of minimum reactor blade angle. This is a fail-safe position assumed by the actuator in the event of electrical power loss.

SECTION V

RELIABILITY, MAINTAINABILITY, AND SAFETY ANALYSES

Reliability and maintainability analyses, and a system safety analysis were performed in compliance with Paragraphs 5.0 and 6.0 of the contract Statement of Work (SOW).

5.1 Reliability Analysis

The contract test program did not provide for accumulating sufficient data for reliability predictions. Therefore, the variable geometry torque converter potential reliability was established by analyzing data accumulated with the basic B-1 torque converter, with appropriate allowance for the additional components in the variable geometry design.

The major additional components required for the variable geometry torque converter are as follows:

- o Actuator shaft and gear assembly
- o Actuator shaft support bearings
- o Actuator shaft seals
- o Actuator shaft load spring
- o 12 vane drive gears
- o 12 variable vane assemblies

Based upon the added components and the variable geometry torque converter operational mode, it is expected that reliability will be not less than an MTBF of 25,000 hours.

5.1.1 Experience with the B-1 Torque Converter

The following time and start cycles have been accumulated by the B-1 Secondary Power Systems without torque converter failure or malfunction. Eighteen units were available for this test program.

Where Accumulated	Hours	Main Engine Start Cycles
B-1 Operation at Edwards AFB	4911	1457
Pre-qualification Endurance Test at AiResearch	539	84
TOTAL FAILURE-FREE EXPERIENCE	5450	1541

The accumulation of 5450 unit hours with zero failures yields a potential MTBF in excess of 54,000 hours at a 90-percent confidence level for the basic B-1 torque converter. This compares favorably with the originally-predicted MTBF of 50,000 hours for this component.

5.1.2 Variable Reactor Torque Converter Reliability Potential

Based on the basic B-1 torque converter and the added complexity of the variable geometry torque converter, it is concluded that the variable geometry torque converter potential MTBF is not less than 25,000 unit hours of service in a system such as the B-1 SPS.

5.2 Maintainability Analysis

This analysis was conducted on a comparative basis. The baseline configuration was the Torque Converter Assembly, Right Hand, Part No. 3607070-1, which is the design used on the redesigned Accessory Drive Gearbox, Right Hand, (ADG, RH) Part

No. 386812-1. This torque converter and gearbox are secondary power subsystem components for B-1 Aircraft 5 and subsequent.

5.2.1 Qualitative Maintainability Comparison

A Comparison Table of Qualitative Maintainability, was constructed and is presented in Table 4:

TABLE 4. COMPARISON TABLE OF QUALITATIVE MAINTAINABILITY

Maintainability Feature	Baseline Torque Converter	Variable Geometry Torque Converter
ON-AIRCRAFT		
Remove and replace without draining gearbox oil	Yes	Yes
Designed for plug-in, stud-supported remove/replace without external fluid or mechanical connections	Yes	No--Fluid connections same as baseline. External mechanical connection for variable geometry control presents moderately significant interference to remove/replace action
Checkout after replacement by simply motoring main propulsion engine	Yes	No--In addition to motoring the main propulsion engine, it must be verified that the variable geometry control and actuation system is performing within normal limits
OFF-AIRCRAFT		
Depot overhaul requires only skills and equipment normally available at that maintenance level	Yes	Yes--Typically, 10-15% additional time is added to the overhaul task because of the extra components in the variable geometry mechanism

5.2.2 Quantitative Maintainability Analysis

A summary type maintenance analysis is provided in Table 5 for the Variable Geometry Torque Converter (VGTC). The analysis covers on-aircraft preventive and corrective maintenance and off-aircraft VGTC overhaul. A brief explanation of certain Table 5 block titles and column headings is included for clarity:

(a) The "Type Maintenance" block indicates where the task is preventive or corrective.

(b) The "TBO" block is Time Between Overhaul for the equipment, if so designated by the inclusion of time limiting components within the VGTC.

(c) The "Random Failure Rate" is the total mean time between failure predicted for the VGTC.

(d) The "Task Description" is Inspect, Repair, Remove, Install, Overhaul, etc. or whatever is required to sufficiently describe all maintenance tasks predicted for the life of the VGTC.

(e) The "Level of Maintenance" column indicates the recommended location for performing the task such as Organizational, Intermediate or Depot.

(f) The "AFSC" column indicates the Air Force Specialty Code used to identify required manpower skills.

(g) The "Crew Size" column indicates the minimum number of technicians recommended to perform the task.

TABLE 5. MAI

NOMENCLATURE: Variable Geometry Torque Converter		PART NO: L-3621704
TYPE MAINTENANCE: Preventive, on-aircraft	TBO: TBD	RANDOM FAILURE RATE:

ASSEMBLY/PART	TASK DESCRIPTION
Variable Geometry Torque Converter (part of B-1 Aircraft Accessory Drive Gearbox)	Scheduled 100 Hour Visual Inspection: Inspect the Accessory Drive Gearbox (ADG), (including Torque Converter) for mounting security, loose or missing components, and physical damage. Verify oil level NOTE: Task shown is for inspecting the entire ADG. No attempt was made to allocate inspection time only to the Variable Geometry Torque Converter.

BLE 5. MAINTENANCE ANALYSIS

4	SPECIFICATION NO: Contract No. F33615-76-C-2013					SHEET 1 OF 1		
RATE:	Scheduled							
	LEVEL OF MAINTENANCE	AFSC	CREW SIZE	ELAPSED TIME (HOURS)	TOTAL MMH PER TASK	FREQUENCY PER 1000 FHRS	MMH PER 1000 FHRS	ELAPSED TIME PER 1000 FHRS
pection: Gearbox nverter) e or sical ecting the ade to to the erter.	Organi- zational	43230	1	0.093	0.093			
				TOTAL MMH	0.093			

2

TABLE 5. MAI

NOMENCLATURE: Variable Geometry Torque Converter		PART NO: L-3621704
TYPE MAINTENANCE: Corrective, on-aircraft	TBO: TBD	RANDOM FAILURE RATE:

ASSEMBLY/PART	TASK DESCRIPTION
Variable Geometry Torque Converter (installed as a part of the B-1 Aircraft Secondary Power Sub-System)	Remove and replace Torque Converter on-aircraft by: (1) Fault isolate to failed torque converter (2) Disconnect and clear torque converter vane control and actuation system (3) Remove and replace variable geometry torque convecter (4) Reconnect and adjust torque converter vane control and actuation system (5) Checkout by starting Auxiliary Power Unit, engaging ADG, and motoring main propulsion engine; verify performance of variable geometry control and actuation system.

5. MAINTENANCE ANALYSIS (Contd)

	SPECIFICATION NO: Contract No. F33615-76-C-2013					SHEET 1 OF 1		
E:	Unscheduled							
	LEVEL OF MAINTENANCE	AFSC	CREW SIZE	ELAPSED TIME (HOURS)	TOTAL MMH PER TASK	FREQUENCY PER 1000 FHRS	MMH PER 1000 FHRS	ELAPSED TIME PER 1000 FHRS
ter								
rque	Organiza-tional	43270 43270	1 1	0.083 0.166	0.083 0.166			
	Organiza-tional	43230	1	0.100	0.100			
	Organiza-tional	43230	1	0.480	0.480			
	Organiza-tional	43230	1	0.150	0.150			
iary and ngine; able tion	Organiza-tional	43230	1	0.150	0.150			
				TOTAL MMH	1.129			

2

TABLE 5. MAIN

NOMENCLATURE:	PART NO:	S
Variable Geometry Torque Converter	L-3621704	

TYPE MAINTENANCE:	TBO:	RANDOM FAILURE RATE:
Corrective, Off-aircraft	TBD	

ASSEMBLY/PART	TASK DESCRIPTION
Variable Geometry Torque Converter	Variable Geometry Torque Converter Overhaul: (1) Inspect for obvious damage, evidence of leakage or metal debris indicating internal failure (visual screening). (Assume 10% in this category) (2) Install torque converters passing visual screening in test fixture and test for performance (mechanical screening). Route foiled units for overhaul. (Assume 20% pass, 70% fail) (3) Disassemble torque converter. (4) Clean and inspect bearings, impellers, stator, stator vanes, shafts, gears and splines. (5) Reassemble torque converter replacing worn or damaged parts, and all packings. Route to final test. (6) Install in test fixture, conduct final test, prepare for storage and return to stock. NOTE: The tasks described are not performed serially, since in a Depot operation, it is assumed that simultaneous task performance by the different AFSC's would be standard operating procedure.

5. MAINTENANCE ANALYSIS (Contd)

	SPECIFICATION NO: Contract No. F33615-76-C-2013	SHEET 1 OF 1
E:	Unscheduled	

	LEVEL OF MAINTENANCE	AFSC	CREW SIZE	ELAPSED TIME (HOURS)	TOTAL MMH PER TASK	FREQUENCY PER 1000 FHRS	MMH PER 1000 FHRS	ELAPSED TIME PER 1000 FHRS
ter								
, al l). ry)	Depot	43270	1	0.10	0.10			
n test rmance Route . l)	Depot	43270	1	0.50	0.50			
ter.	Depot	43250	1	2.50	2.50			
, vanes, .	Depot	43270	1	0.70	0.70			
r parts, to	Depot	43250	1	3.70	3.70			
conduct torage	Depot	43270	1	0.70	0.70			
				TOTAL MMH	8.20			
not Depot simulta- different ting								

2

(h) The "Elapsed Time" column tabulates the direct labor clock hours estimated for performing each task, while the "Total Maintenance Manhours (MMH) per Task" column takes account of "Elapsed Time" and "Crew Size."

(i) The "Frequency per 1000 Flight Hours (FHRS)" column is used to show the predicted interval between maintenance tasks.

5.2.3 Quantitative Maintainability Comparison

Maintainability data has previously been prepared on the baseline configuration torque converter earlier described. With those parameters and the data provided in Table 5, it was possible to make a direct comparison of maintenance man-hours (MMH) to accomplish identical tasks on the Baseline Torque Converter and the Variable Geometry Torque Converter. The comparison is shown in Tables 6 and 7.

TABLE 6. ON-AIRCRAFT QUANTITATIVE MAINTAINABILITY COMPARISON

Task	Baseline Torque Converter	Variable Geometry Torque Converter
Scheduled 100 Hour Visual Inspection	0.093 MMH	0.093 MMH
Remove and Replace Torque Converter	0.70 MMH	1.129 MMH

TABLE 7. OFF-AIRCRAFT QUANTITATIVE MAINTAINABILITY COMPARISON

Task	Baseline Torque Converter	Variable Geometry Torque Converter
Overhaul at Depot	7.3 MMH*	8.2 MMH

*Original data did not include screening activity shown in Table II. Screening activity was added to allow direct comparison (6.7 MMH + 0.6 MMH) original + screening)

5.3 System Safety

5.3.1 Safety Organization, Responsibilities, and Authority

AiResearch Operational Procedures 10.35 and 2.57 specify organizational responsibilities for safety at AiResearch. The Director of Product Integrity is responsible for (1) monitoring and coordinating policies and procedures related to System Safety, and (2) ensuring overall effectiveness of methods for complying with applicable portions of MIL-STD-882.

The Engineering Project is also responsible for inherent safety in the product design and has primary responsibility for defining and conducting the Safety Program as it affects product design. Other departments may be required to appoint safety monitors for a program with responsibility to work within the scope of the Safety Plan for resolution of safety problems affecting their departments.

Among other functions, the AiResearch Product Integrity Committee is responsible for final resolution of conflicts concerning safety that may arise within a program.

5.3.2 System Safety Analysis

Although a Failure Modes and Effect Analysis was not included in this program contract, an FMEA on a similar torque converter was examined. It was determined that no MIL-STD-882

category III or IV hazards exist. An abbreviated safety analysis is presented in Table 8.

TABLE 8. ABBREVIATED SAFETY ANALYSIS

Potential Hazard	Anticipated Method of Control
Bearing seizure (driving section and driven section)	Proper bearing design, adequate lubrication and quality control.
Rotating elements locked rogether	Proper design and retention of elements.
Overspeed	Design elements to safely withstand maximum overspeed possible from either input or output.
Variable reactor vane assembly failure	Designed for following: Failed Open - imposes higher than normal load to input power source. (Probably will cause overload shutdown.) Failed Closed - Imposes less than normal load to input power source.
Actuator shaft assembly failure	Designed so that if retention nut or spring fails, secondary retention device will prevent disengagement of actuator gears or rubbing of elements.

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The fabrication and testing conducted during this program has demonstrated the feasibility of utilizing a variable reactor in a high-speed torque converter to modulate power output from a gas turbine engine. A simple control system can be devised and utilized in conjunction with normal control components in use on current APU.

6.2 Recommendations

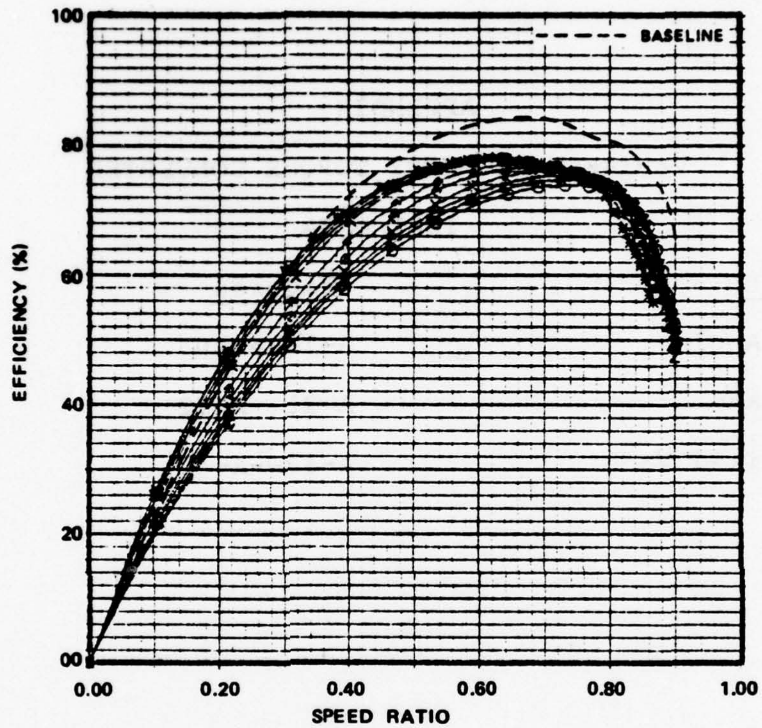
It is recommended that the original program goals be demonstrated by supplementing the current program. A new variable reactor vane design is required that will produce flow angles similar to those of the fixed B-1 reactor. Some relaxation from the existing B-1 flowpath is probably required. Testing this configuration could indicate the extent to which power can be decreased with a practical variable reactor

APPENDIX

VARIABLE GEOMETRY TORQUE CONVERTER

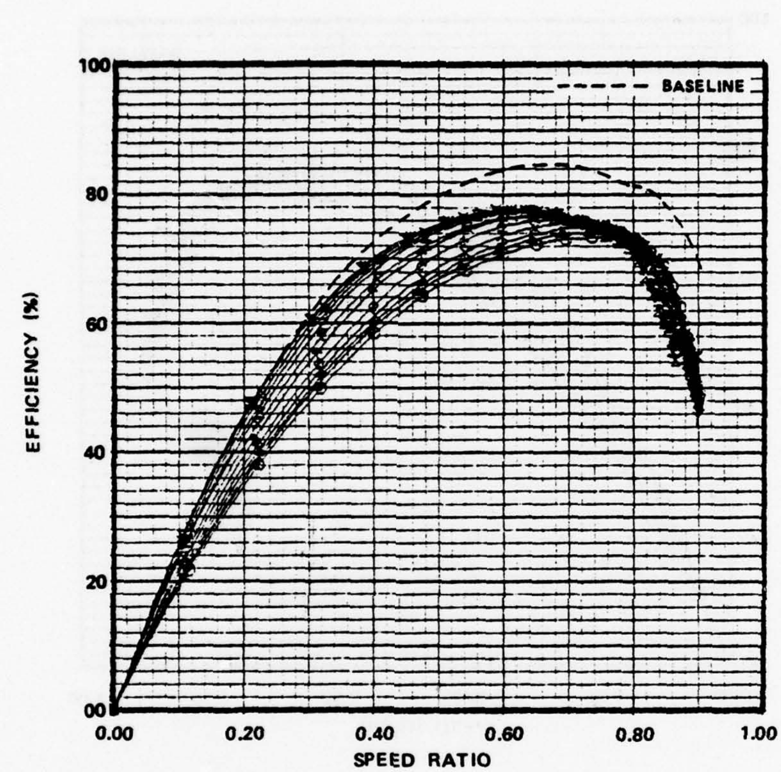
TEST DATA

Test	Figures	Pages
Fixed Vane Angle	A-1--A-20	106-125
Modulated Vane	A-21--A-32	126-137
Over-Open Fixed Vane	A-33--A-42	138-147



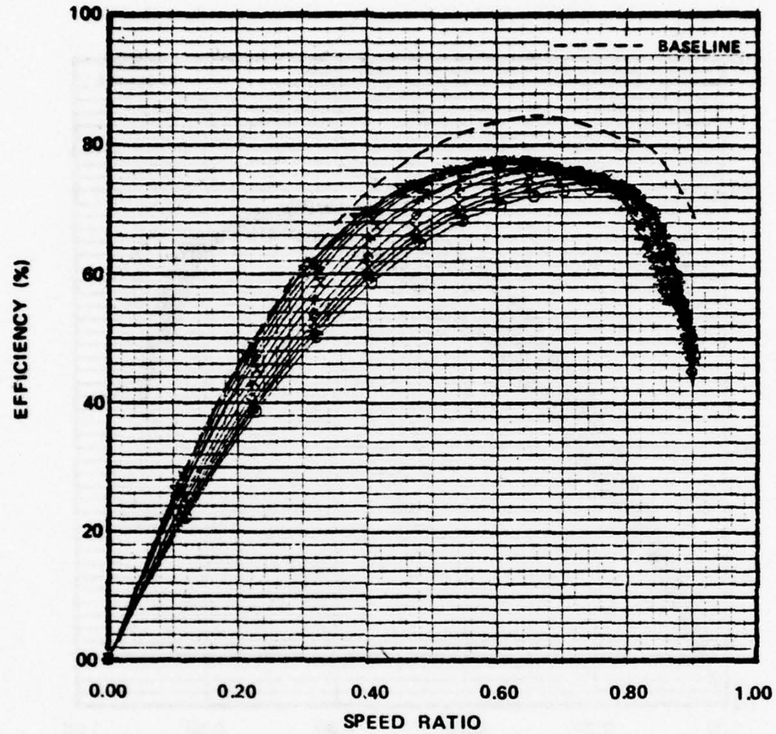
O	PRESSURE = 309.8	LBS/SQ. IN. ABS.	REACTOR ANGLE = 0.0
Δ	PRESSURE = 315.0	LBS/SQ. IN. ABS.	2.5
+	PRESSURE = 315.7	LBS/SQ. IN. ABS.	5.0
✕	PRESSURE = 311.8	LBS/SQ. IN. ABS.	7.5
◇	PRESSURE = 308.2	LBS/SQ. IN. ABS.	10.0
♀	PRESSURE = 320.9	LBS/SQ. IN. ABS.	12.5
X	PRESSURE = 322.5	LBS/SQ. IN. ABS.	17.5
Z	PRESSURE = 328.1	LBS/SQ. IN. ABS.	20.0
Y	PRESSURE = 317.5	LBS/SQ. IN. ABS.	22.5
⌑	PRESSURE = 317.0	LBS/SQ. IN. ABS.	25.0
✳	PRESSURE = 315.0	LBS/SQ. IN. ABS.	27.5

Figure A-1. Fixed vane angle test--efficiency @ 300 psig.



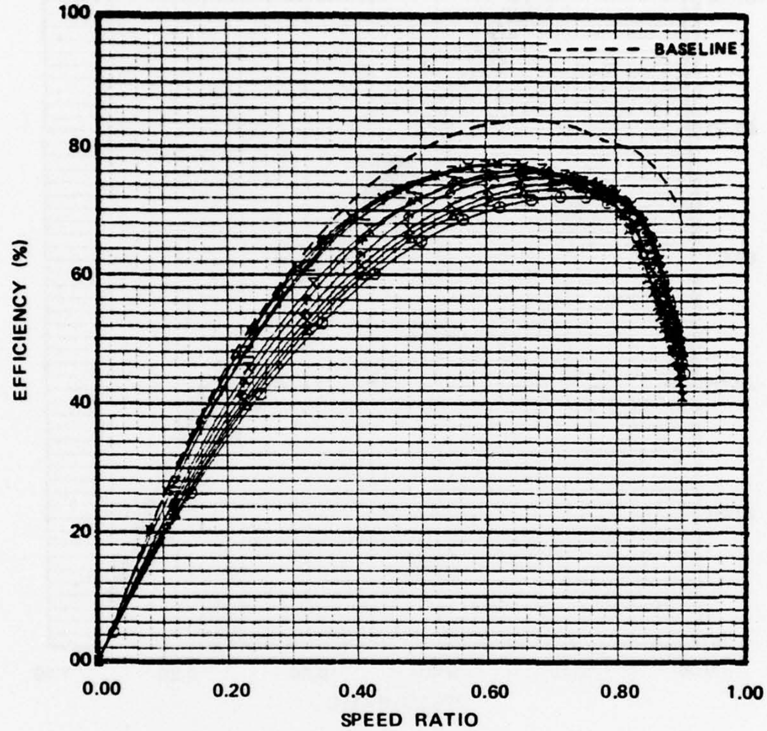
○	PRESSURE = 409.4 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△	PRESSURE = 406.8 LBS/SQ. IN. ABS.		2.5
+	PRESSURE = 421.8 LBS/SQ. IN. ABS.		5.0
✖	PRESSURE = 395.0 LBS/SQ. IN. ABS.		7.5
◇	PRESSURE = 416.9 LBS/SQ. IN. ABS.		10.0
⯊	PRESSURE = 401.2 LBS/SQ. IN. ABS.		12.5
X	PRESSURE = 425.0 LBS/SQ. IN. ABS.		15.0
Z	PRESSURE = 399.9 LBS/SQ. IN. ABS.		17.5
Y	PRESSURE = 418.5 LBS/SQ. IN. ABS.		20.0
¤	PRESSURE = 393.4 LBS/SQ. IN. ABS.		22.5
✱	PRESSURE = 379.3 LBS/SQ. IN. ABS.		25.0
⧖	PRESSURE = 414.2 LBS/SQ. IN. ABS.		27.5

Figure A-2. Fixed vane angle test--efficiency @ 400 psig.



○	PRESSURE = 456.1 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△	PRESSURE = 471.7 LBS/SQ. IN. ABS.		2.5
+	PRESSURE = 468.8 LBS/SQ. IN. ABS.		5.0
✕	PRESSURE = 455.4 LBS/SQ. IN. ABS.		7.5
◇	PRESSURE = 463.9 LBS/SQ. IN. ABS.		10.0
↑	PRESSURE = 464.5 LBS/SQ. IN. ABS.		12.5
X	PRESSURE = 433.2 LBS/SQ. IN. ABS.		15.0
Z	PRESSURE = 463.2 LBS/SQ. IN. ABS.		17.5
Y	PRESSURE = 467.5 LBS/SQ. IN. ABS.		20.0
⌑	PRESSURE = 444.3 LBS/SQ. IN. ABS.		22.5
✱	PRESSURE = 455.1 LBS/SQ. IN. ABS.		25.0
⧖	PRESSURE = 432.2 LBS/SQ. IN. ABS.		27.5

Figure A-3. Fixed vane angle test--efficiency @ 450 psig.



○ PRESSURE = 497.2 LBS/SQ. IN. ABS. REACTOR ANGLE = 0.1
△ PRESSURE = 520.1 LBS/SQ. IN. ABS. 2.5
+ PRESSURE = 504.7 LBS/SQ. IN. ABS. 5.0
⌘ PRESSURE = 512.5 LBS/SQ. IN. ABS. 7.5
◇ PRESSURE = 496.5 LBS/SQ. IN. ABS. 10.0
⇧ PRESSURE = 508.3 LBS/SQ. IN. ABS. 12.5
X PRESSURE = 492.0 LBS/SQ. IN. ABS. 15.0
Z PRESSURE = 509.6 LBS/SQ. IN. ABS. 20.0
Y PRESSURE = 523.3 LBS/SQ. IN. ABS. 22.5
¤ PRESSURE = 510.2 LBS/SQ. IN. ABS. 25.0
✳ PRESSURE = 505.0 LBS/SQ. IN. ABS. 27.5

Figure A-4. Fixed vane angle test--efficiency @ 500 psig.

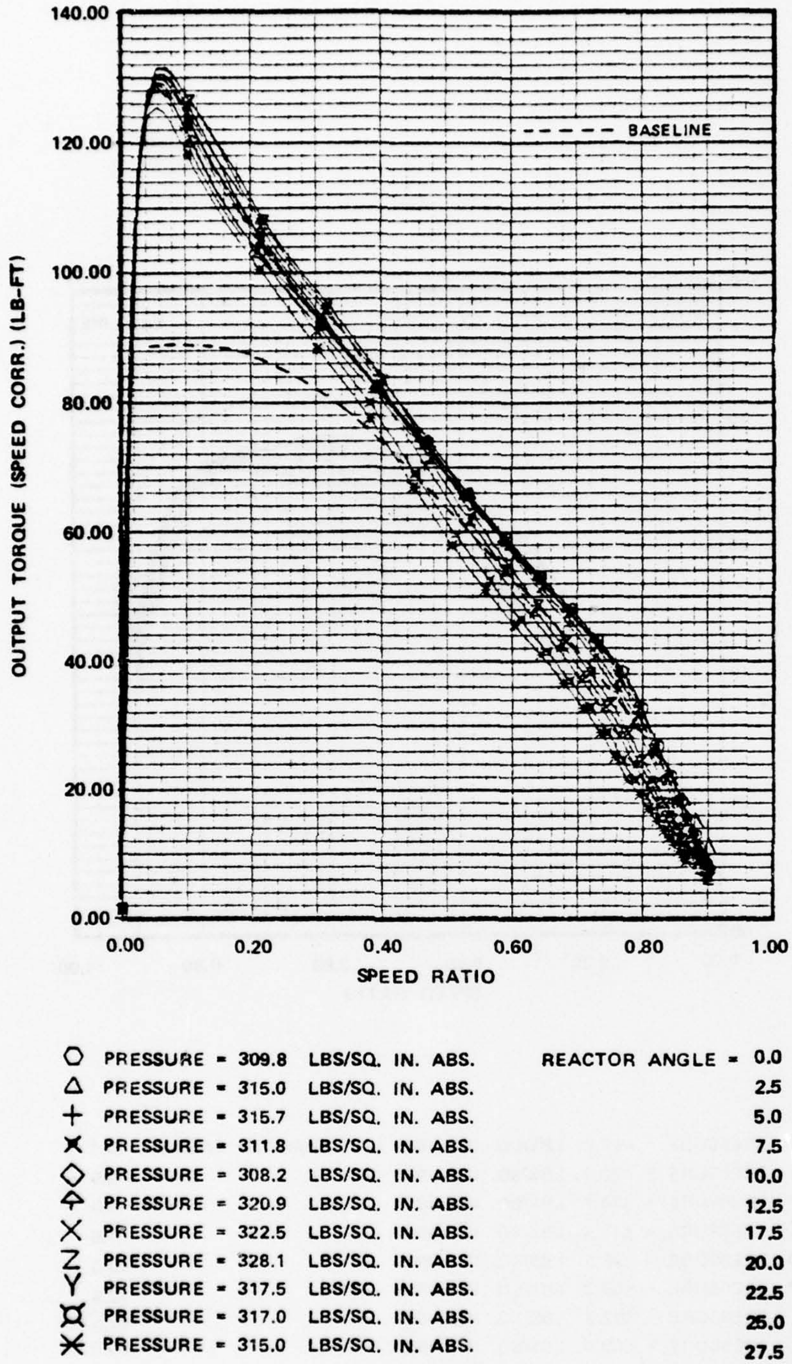
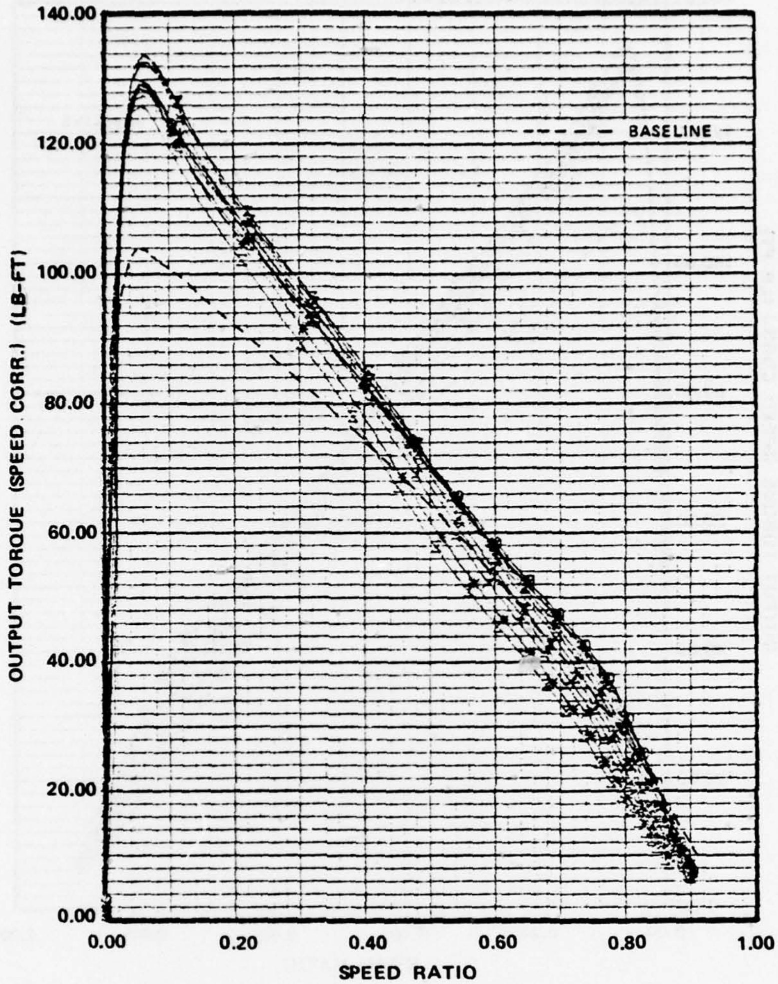
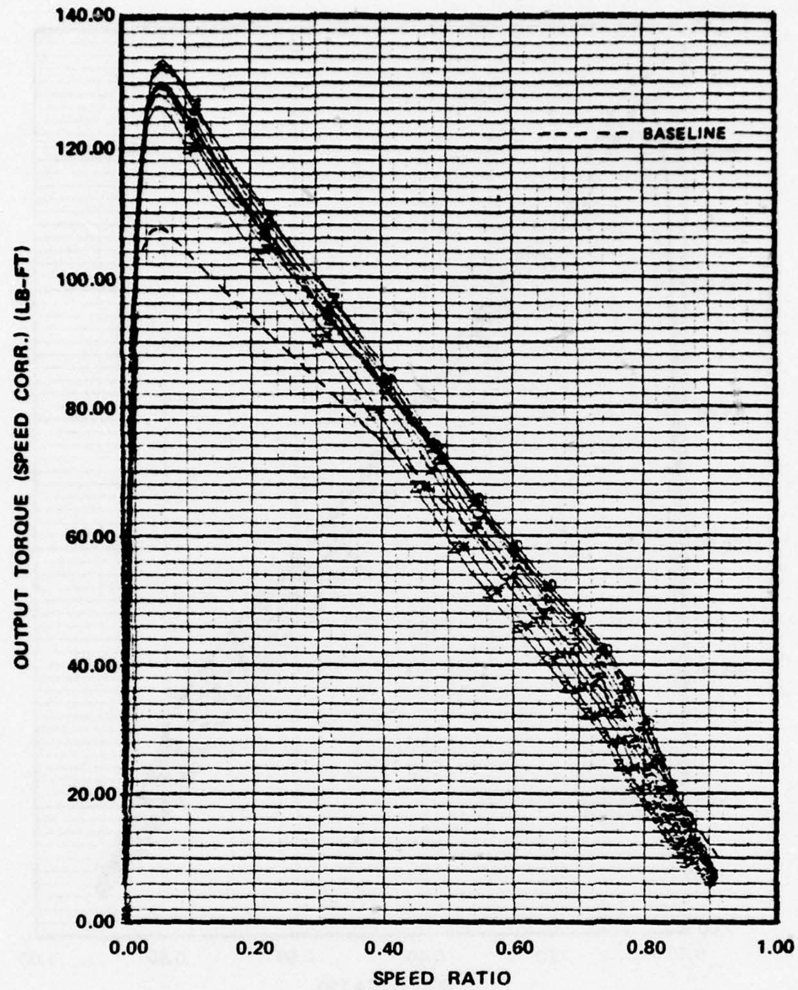


Figure A-5. Fixed vane angle test--output torque @ 300 psig.



○ PRESSURE = 409.4 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△ PRESSURE = 406.8 LBS/SQ. IN. ABS.		2.5
+ PRESSURE = 421.8 LBS/SQ. IN. ABS.		5.0
✗ PRESSURE = 395.0 LBS/SQ. IN. ABS.		7.5
◇ PRESSURE = 416.9 LBS/SQ. IN. ABS.		10.0
⇡ PRESSURE = 401.2 LBS/SQ. IN. ABS.		12.5
X PRESSURE = 425.0 LBS/SQ. IN. ABS.		15.0
Z PRESSURE = 399.9 LBS/SQ. IN. ABS.		17.5
Y PRESSURE = 418.5 LBS/SQ. IN. ABS.		20.0
¤ PRESSURE = 393.4 LBS/SQ. IN. ABS.		22.5
✳ PRESSURE = 379.3 LBS/SQ. IN. ABS.		25.0
⧖ PRESSURE = 414.2 LBS/SQ. IN. ABS.		27.5

Figure A-6. Fixed vane angle test--output torque @ 400 psig.



○	PRESSURE = 456.1 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△	PRESSURE = 471.7 LBS/SQ. IN. ABS.		2.5
+	PRESSURE = 468.8 LBS/SQ. IN. ABS.		5.0
✕	PRESSURE = 455.4 LBS/SQ. IN. ABS.		7.5
◇	PRESSURE = 463.9 LBS/SQ. IN. ABS.		10.0
⯑	PRESSURE = 464.5 LBS/SQ. IN. ABS.		12.5
X	PRESSURE = 433.2 LBS/SQ. IN. ABS.		15.0
Z	PRESSURE = 463.2 LBS/SQ. IN. ABS.		17.5
Y	PRESSURE = 467.5 LBS/SQ. IN. ABS.		20.0
⌑	PRESSURE = 444.3 LBS/SQ. IN. ABS.		22.5
✱	PRESSURE = 455.1 LBS/SQ. IN. ABS.		25.0
⧖	PRESSURE = 432.2 LBS/SQ. IN. ABS.		27.5

Figure A-7. Fixed vane angle test--output torque @ 450 psig.

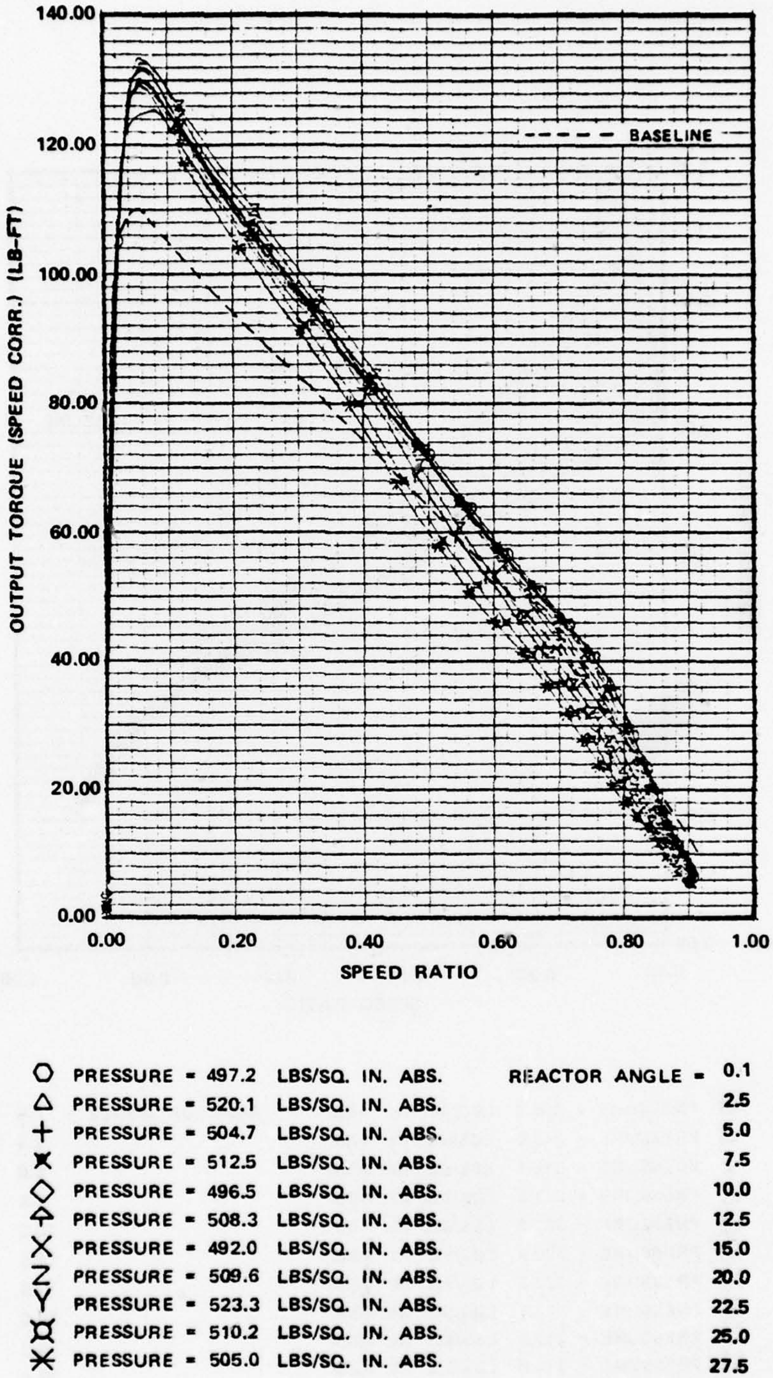


Figure A-8. Fixed vane angle test--output torque @ 500 psig.

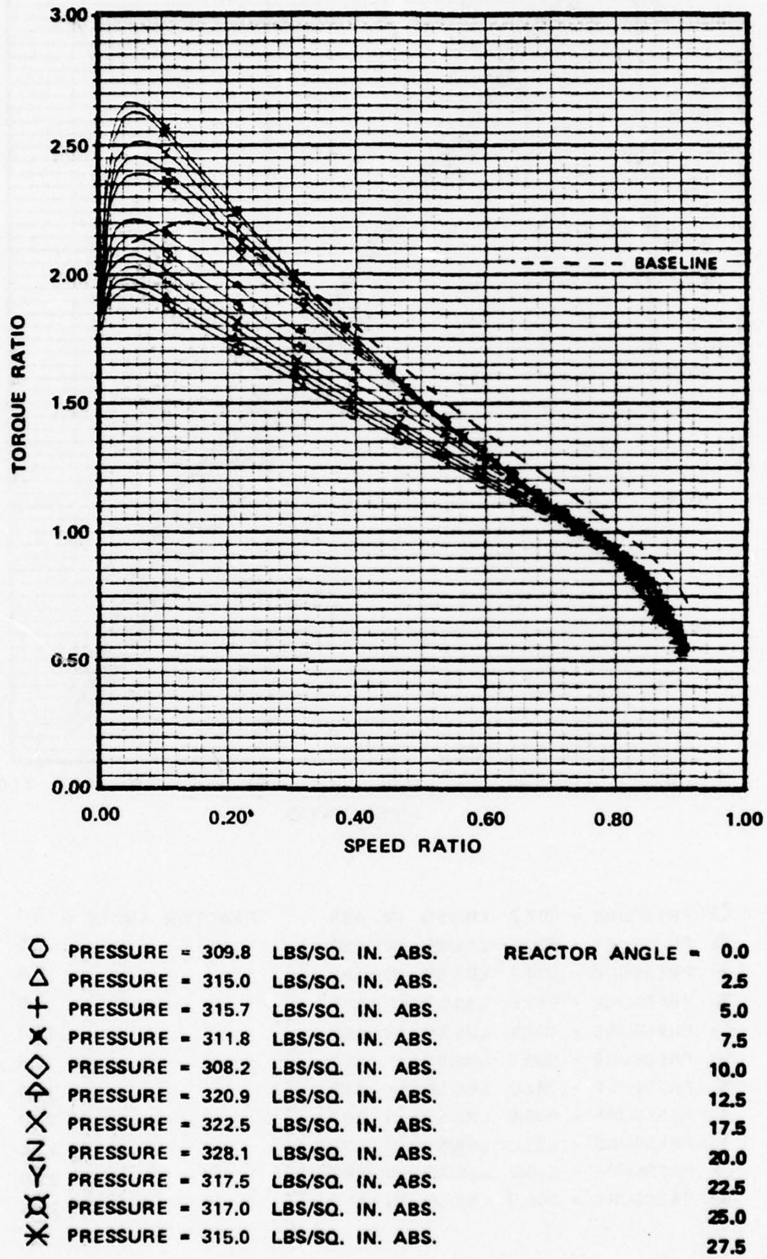
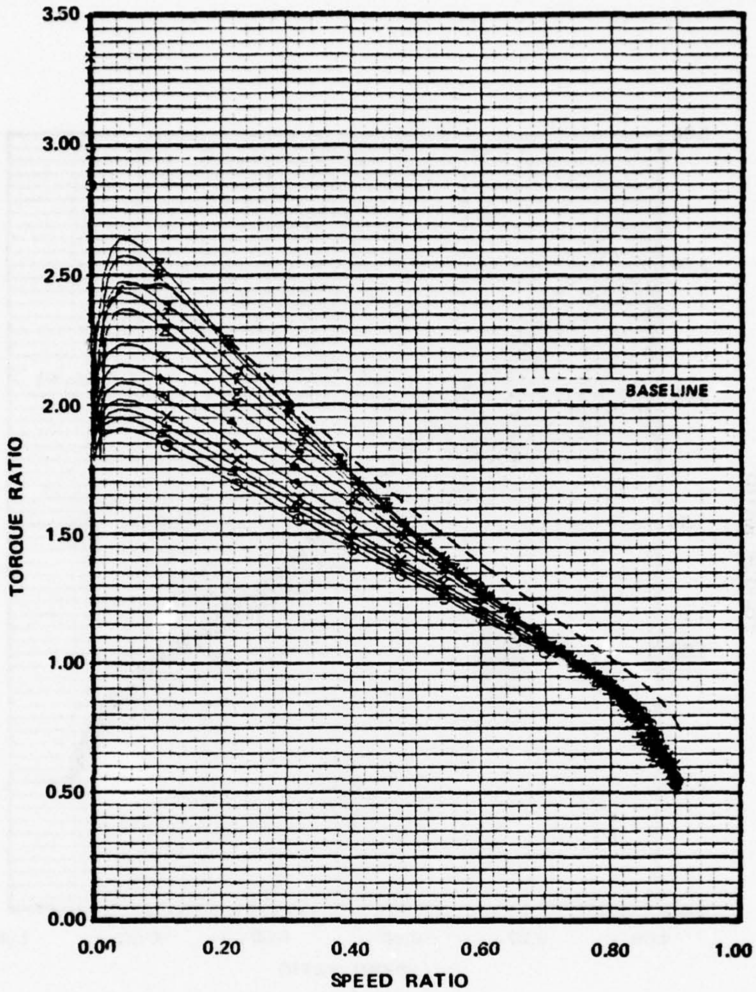
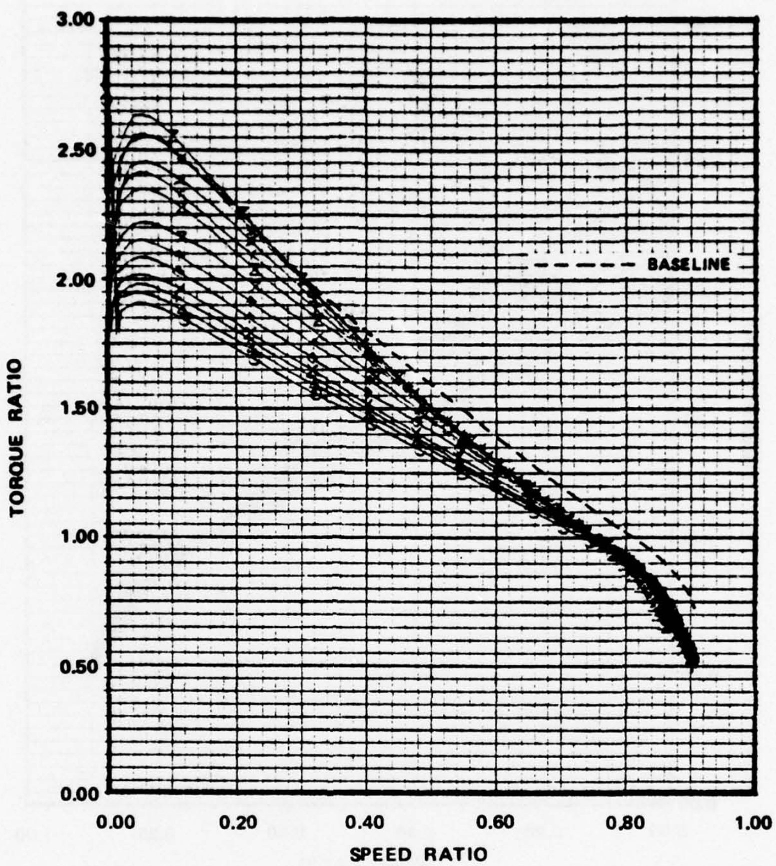


Figure A-9. Fixed vane angle test--torque ratio @ 300 psig.



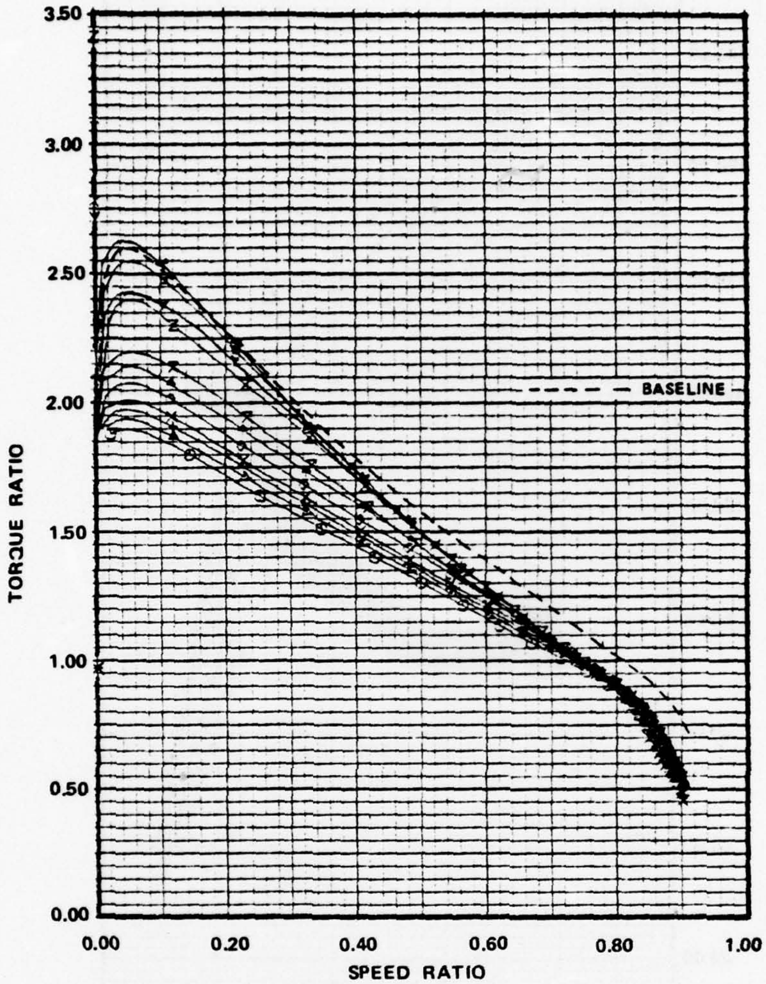
○ PRESSURE = 409.4 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△ PRESSURE = 406.8 LBS/SQ. IN. ABS.		2.5
+ PRESSURE = 421.8 LBS/SQ. IN. ABS.		5.0
✕ PRESSURE = 395.0 LBS/SQ. IN. ABS.		7.5
◇ PRESSURE = 416.9 LBS/SQ. IN. ABS.		10.0
↑ PRESSURE = 401.2 LBS/SQ. IN. ABS.		12.5
X PRESSURE = 425.0 LBS/SQ. IN. ABS.		15.0
Z PRESSURE = 399.9 LBS/SQ. IN. ABS.		17.5
Y PRESSURE = 418.5 LBS/SQ. IN. ABS.		20.0
⌑ PRESSURE = 393.4 LBS/SQ. IN. ABS.		22.5
✳ PRESSURE = 379.3 LBS/SQ. IN. ABS.		25.0
⧖ PRESSURE = 414.2 LBS/SQ. IN. ABS.		27.5

Figure A-10. Fixed vane angle test--torque ratio @ 400 psig.



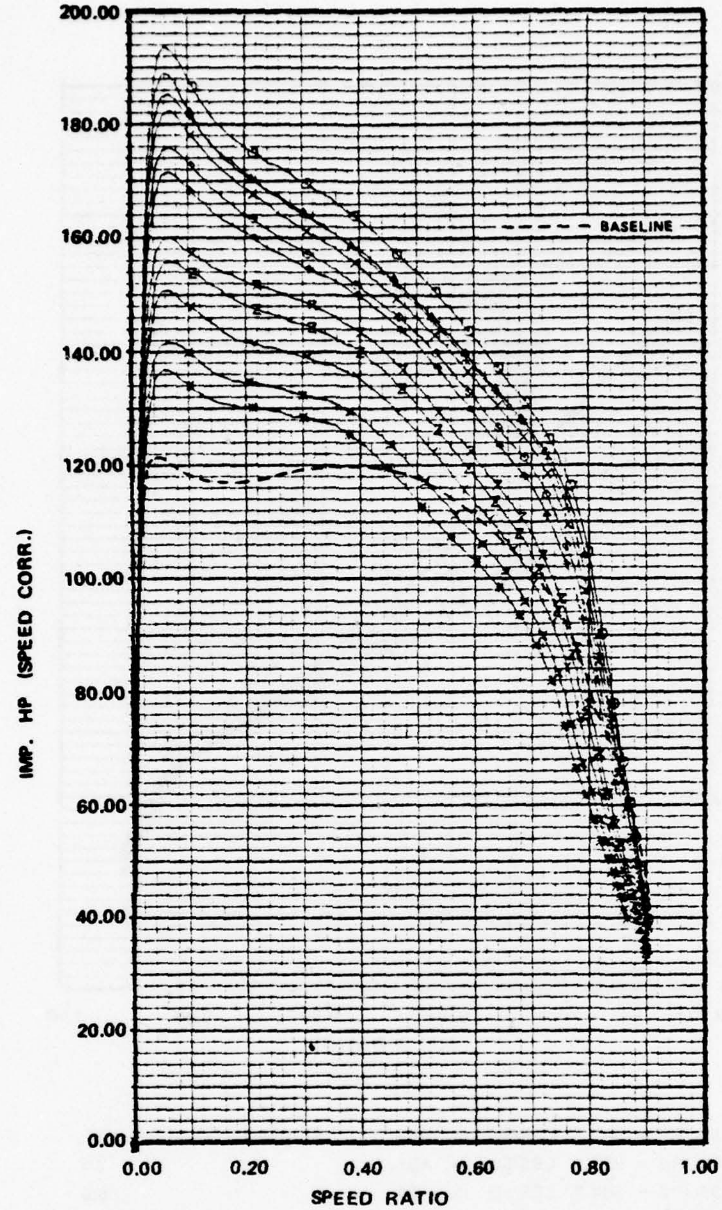
O	PRESSURE = 456.1 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
Δ	PRESSURE = 471.7 LBS/SQ. IN. ABS.		2.5
+	PRESSURE = 468.8 LBS/SQ. IN. ABS.		5.0
×	PRESSURE = 455.4 LBS/SQ. IN. ABS.		7.5
◇	PRESSURE = 463.9 LBS/SQ. IN. ABS.		10.0
↑	PRESSURE = 464.5 LBS/SQ. IN. ABS.		12.5
X	PRESSURE = 433.2 LBS/SQ. IN. ABS.		15.0
Z	PRESSURE = 463.2 LBS/SQ. IN. ABS.		17.5
Y	PRESSURE = 467.5 LBS/SQ. IN. ABS.		20.0
⌧	PRESSURE = 444.3 LBS/SQ. IN. ABS.		22.5
✳	PRESSURE = 455.1 LBS/SQ. IN. ABS.		25.0
⧖	PRESSURE = 432.2 LBS/SQ. IN. ABS.		27.5

Figure A-11. Fixed vane angle test--torque ratio @ 450 psig.



○	PRESSURE = 497.2 LBS/SQ. IN. ABS.	REACTOR ANGLE = 0.1
△	PRESSURE = 520.1 LBS/SQ. IN. ABS.	2.5
+	PRESSURE = 504.7 LBS/SQ. IN. ABS.	5.0
✖	PRESSURE = 512.5 LBS/SQ. IN. ABS.	7.5
◇	PRESSURE = 496.5 LBS/SQ. IN. ABS.	10.0
↑	PRESSURE = 508.3 LBS/SQ. IN. ABS.	12.5
X	PRESSURE = 492.0 LBS/SQ. IN. ABS.	15.0
Z	PRESSURE = 509.6 LBS/SQ. IN. ABS.	20.0
Y	PRESSURE = 523.3 LBS/SQ. IN. ABS.	22.5
¤	PRESSURE = 510.2 LBS/SQ. IN. ABS.	25.0
✳	PRESSURE = 505.0 LBS/SQ. IN. ABS.	27.5

Figure A-12. Fixed vane angle test--torque ratio @ 500 psig.



○ PRESSURE = 309.8	LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△ PRESSURE = 315.0	LBS/SQ. IN. ABS.		2.5
+ PRESSURE = 315.7	LBS/SQ. IN. ABS.		5.0
✕ PRESSURE = 311.8	LBS/SQ. IN. ABS.		7.5
◇ PRESSURE = 308.2	LBS/SQ. IN. ABS.		10.0
♀ PRESSURE = 320.9	LBS/SQ. IN. ABS.		12.5
X PRESSURE = 322.5	LBS/SQ. IN. ABS.		17.5
Z PRESSURE = 328.1	LBS/SQ. IN. ABS.		20.0
Y PRESSURE = 317.5	LBS/SQ. IN. ABS.		22.5
¤ PRESSURE = 317.0	LBS/SQ. IN. ABS.		25.0
✱ PRESSURE = 315.0	LBS/SQ. IN. ABS.		27.5

Figure A-13. Fixed vane angle test--impeller hp @ 300 psig.

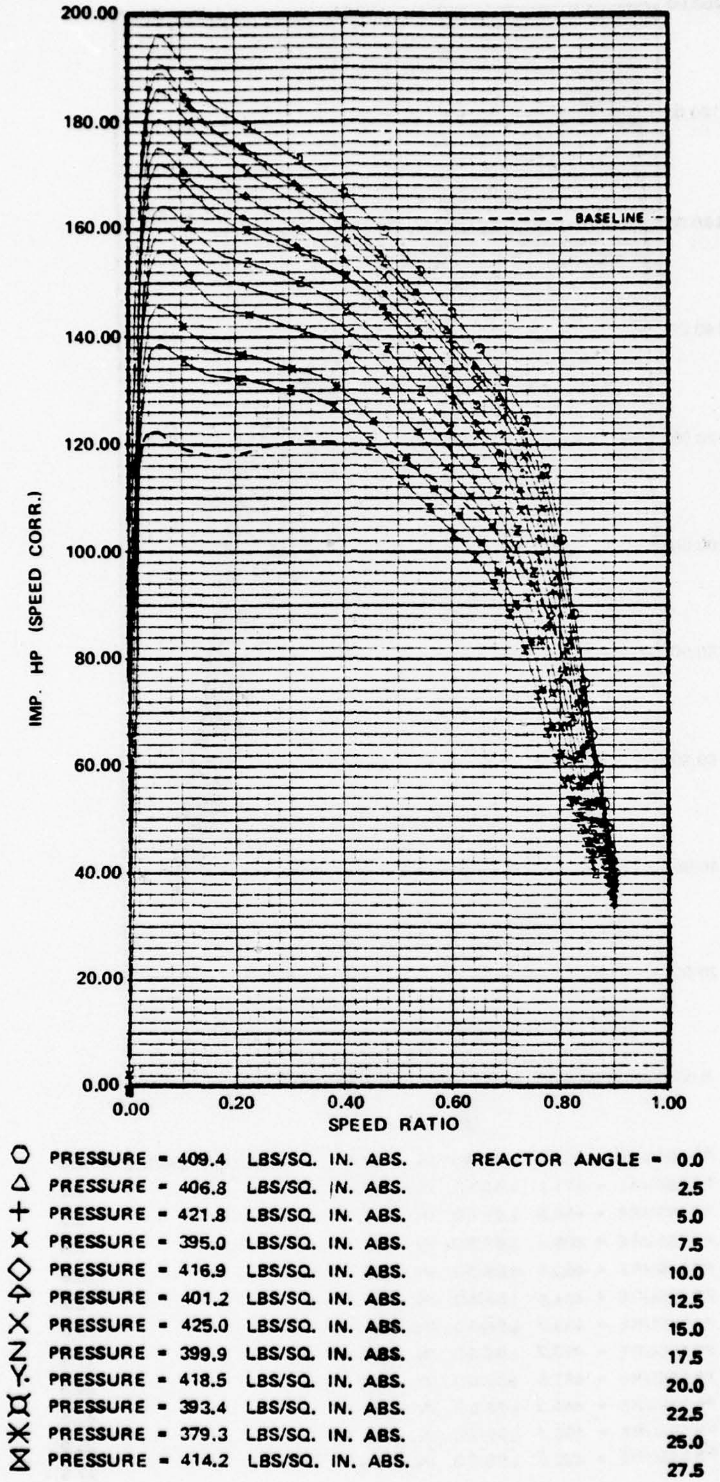


Figure A-14. Fixed vane angle test--impeller hp @ 400 psig.

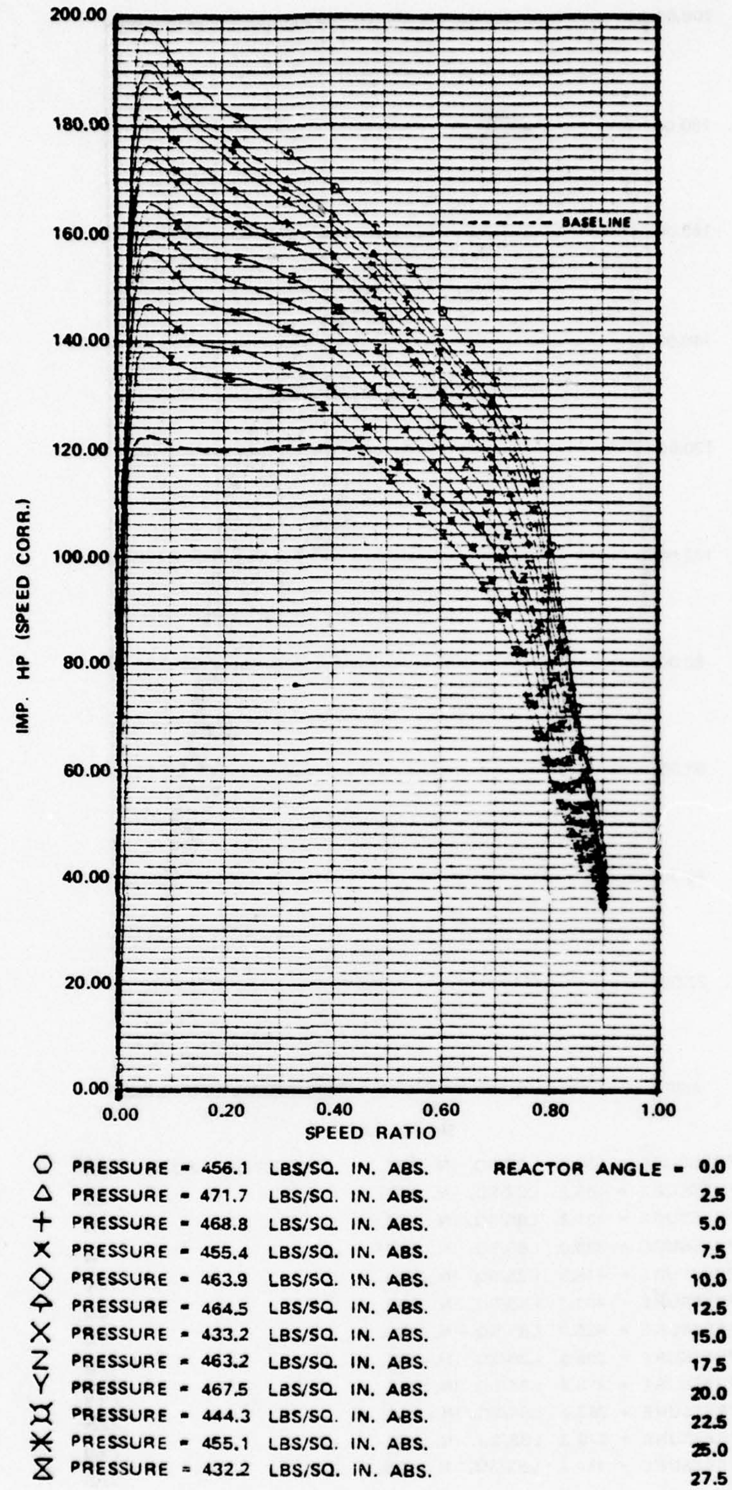


Figure A-15. Fixed vane angle test--impeller hp @ 450 psig.

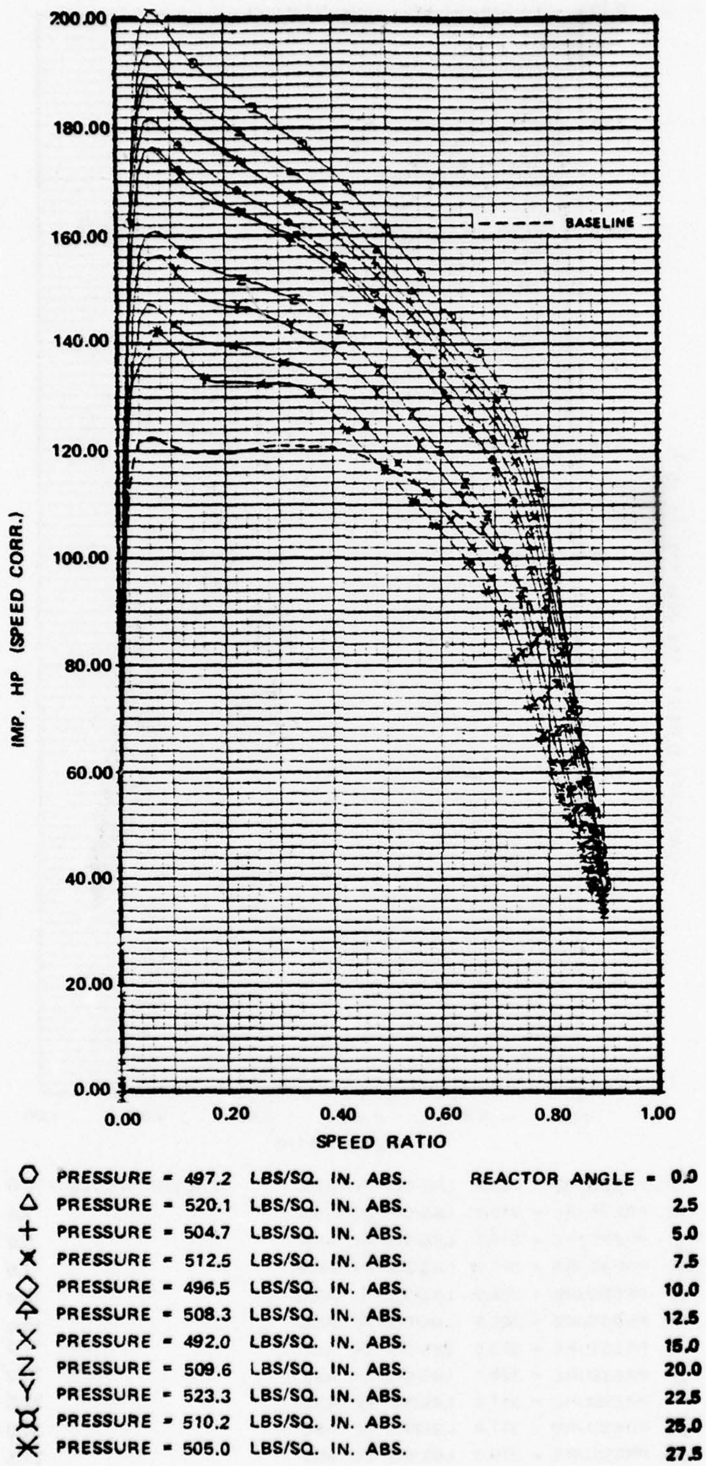


Figure A-16. Fixed vane angle test--impeller hp @ 500 psig.

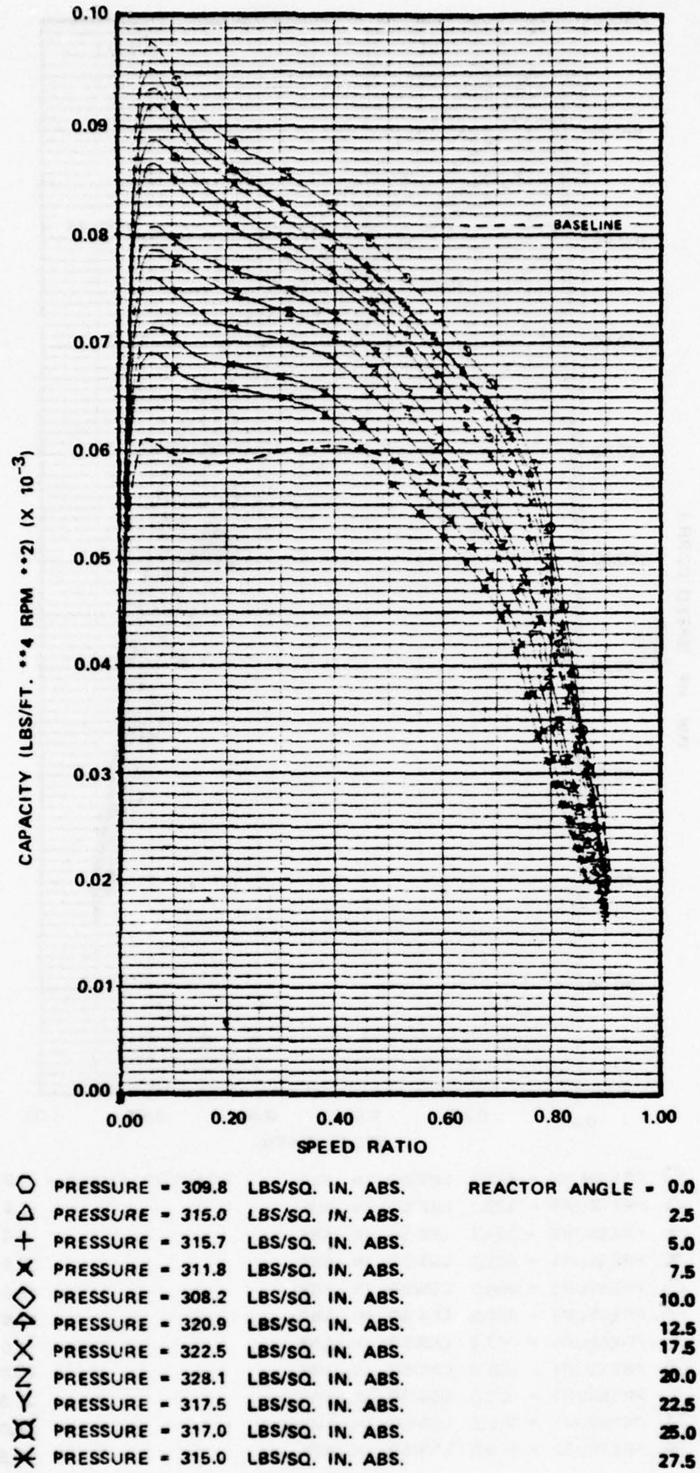
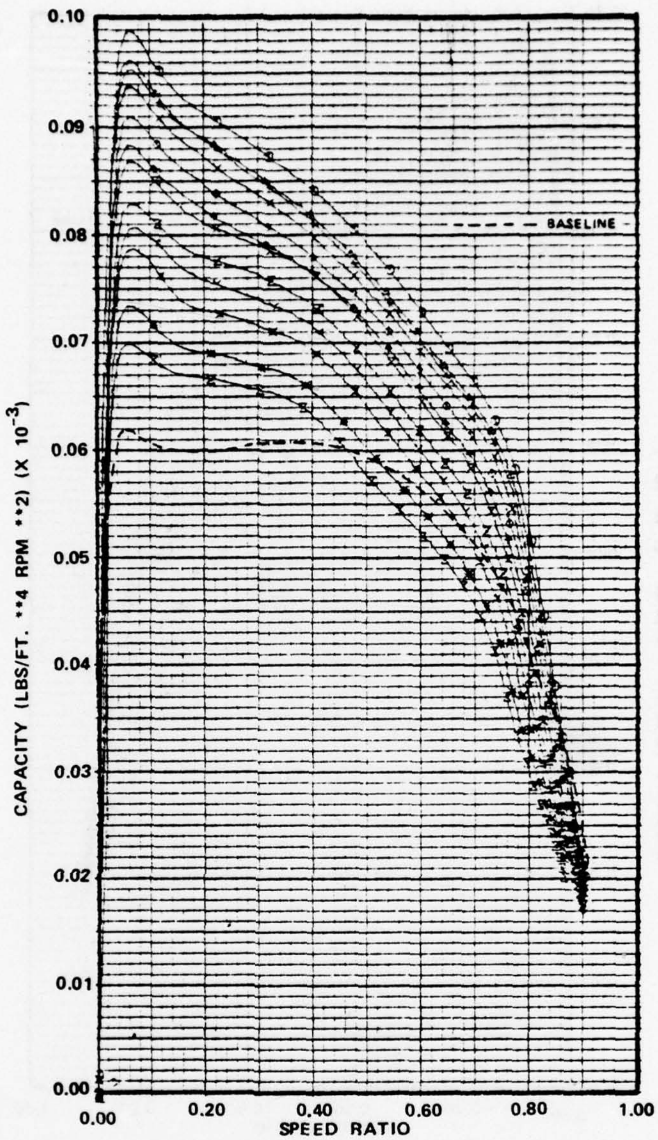


Figure A-17. Fixed vane angle test--impeller hp @ 300 psig.



○	PRESSURE = 456.1	LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.0
△	PRESSURE = 471.7	LBS/SQ. IN. ABS.		2.5
+	PRESSURE = 468.8	LBS/SQ. IN. ABS.		5.0
✕	PRESSURE = 455.4	LBS/SQ. IN. ABS.		7.5
◇	PRESSURE = 463.9	LBS/SQ. IN. ABS.		10.0
◇	PRESSURE = 464.5	LBS/SQ. IN. ABS.		12.5
X	PRESSURE = 433.2	LBS/SQ. IN. ABS.		15.0
Z	PRESSURE = 463.2	LBS/SQ. IN. ABS.		17.5
Y	PRESSURE = 467.5	LBS/SQ. IN. ABS.		20.0
¤	PRESSURE = 444.3	LBS/SQ. IN. ABS.		22.5
✳	PRESSURE = 455.1	LBS/SQ. IN. ABS.		25.0
⧖	PRESSURE = 432.2	LBS/SQ. IN. ABS.		27.5

Figure A-18. Fixed vane angle test--capacity @ 400 psig.

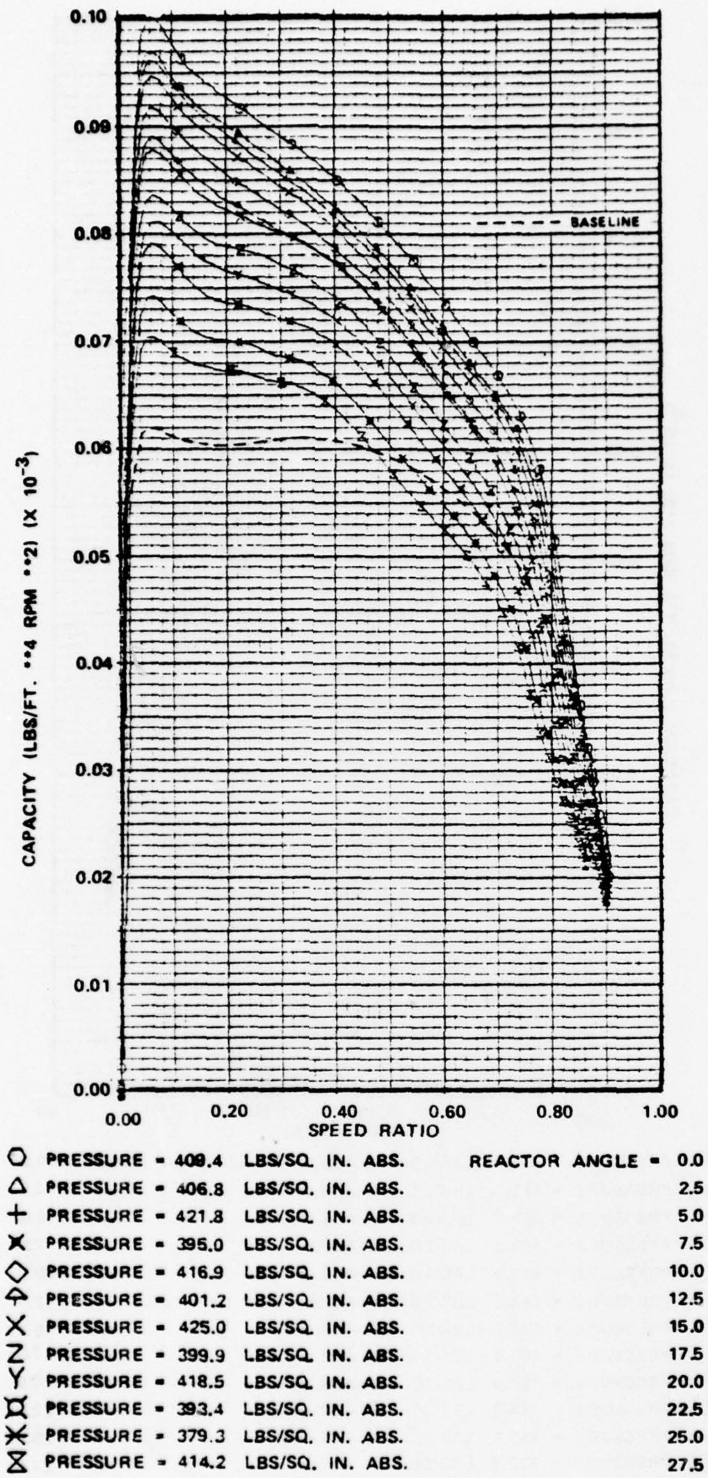


Figure A-19. Fixed vane angle test--capacity @ 450 psig.

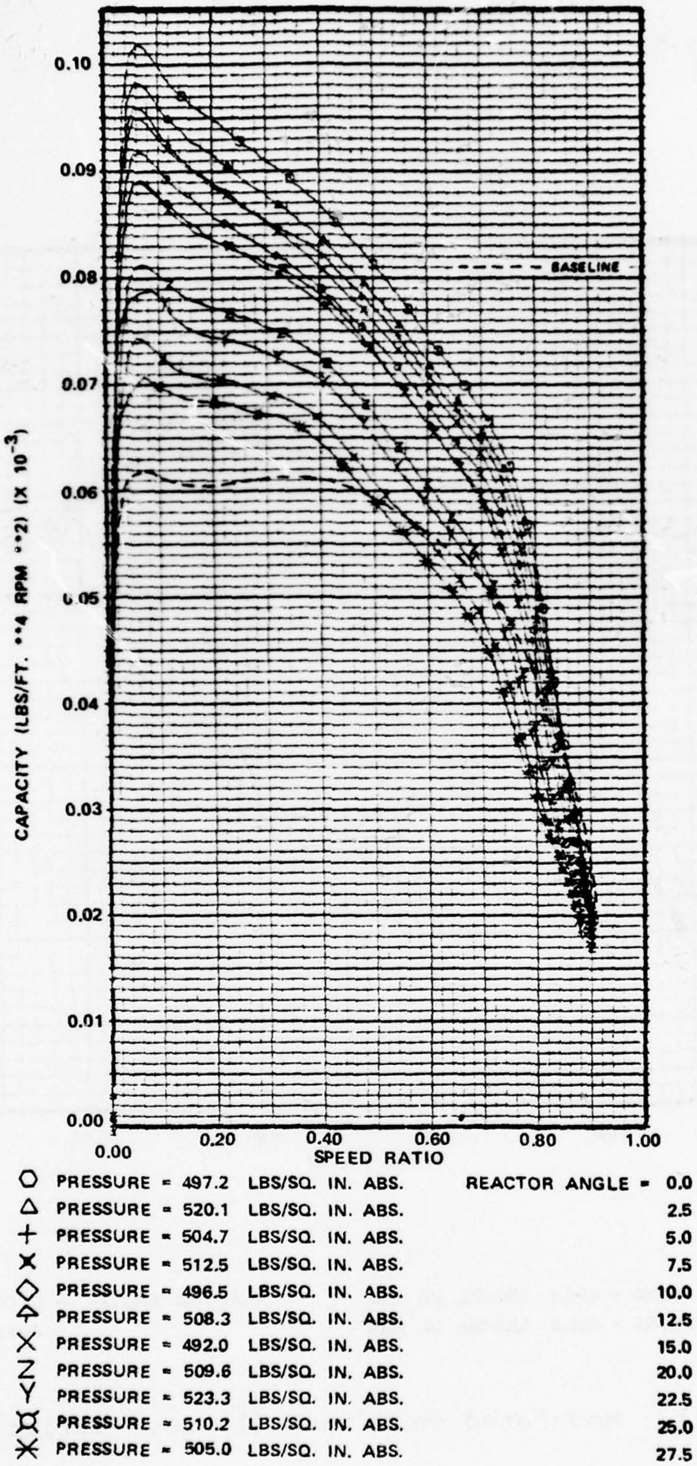
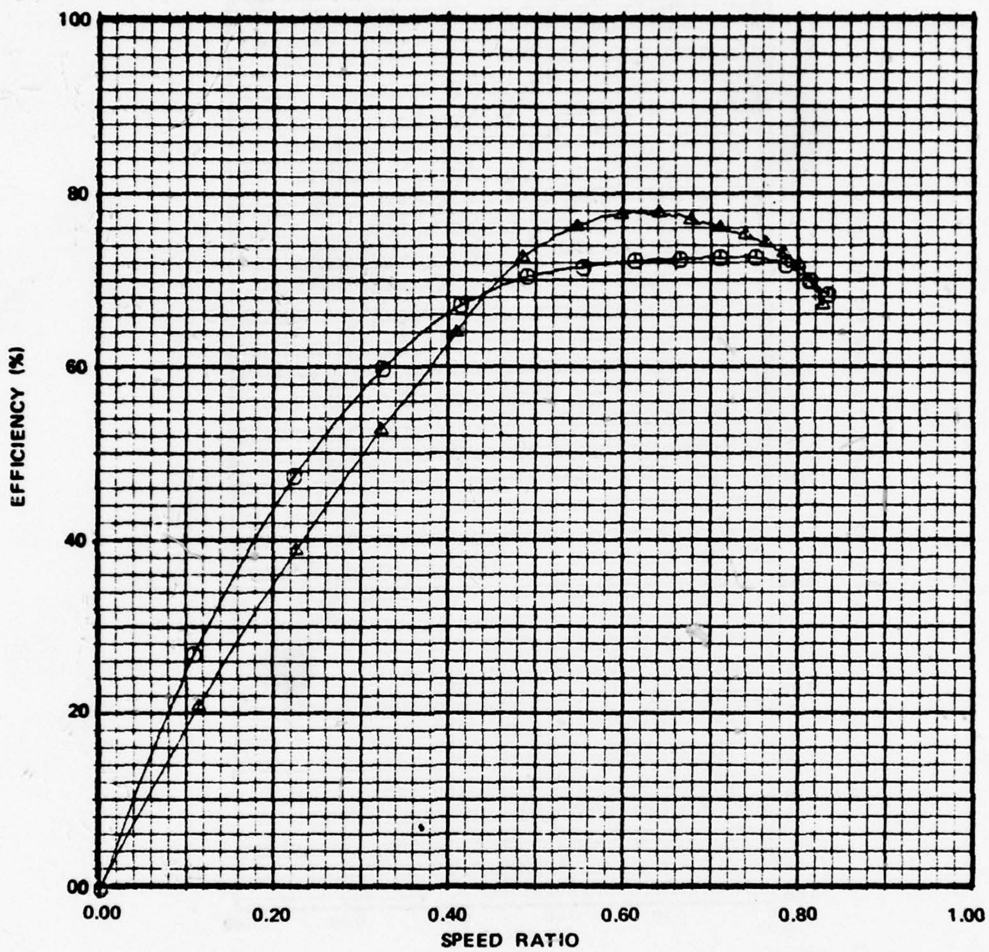


Figure A-20. Fixed vane angle test--capacity @ 500 psig.



O PRESSURE = 456.3 LBS/SQ. IN. ABS.	REACTOR ANGLE	=	CLOSED-TO-OPEN
△ PRESSURE = 465.8 LBS/SQ. IN. ABS.			OPEN-TO-CLOSED

Figure A-21. Modulated vane test (15 sec) efficiency.

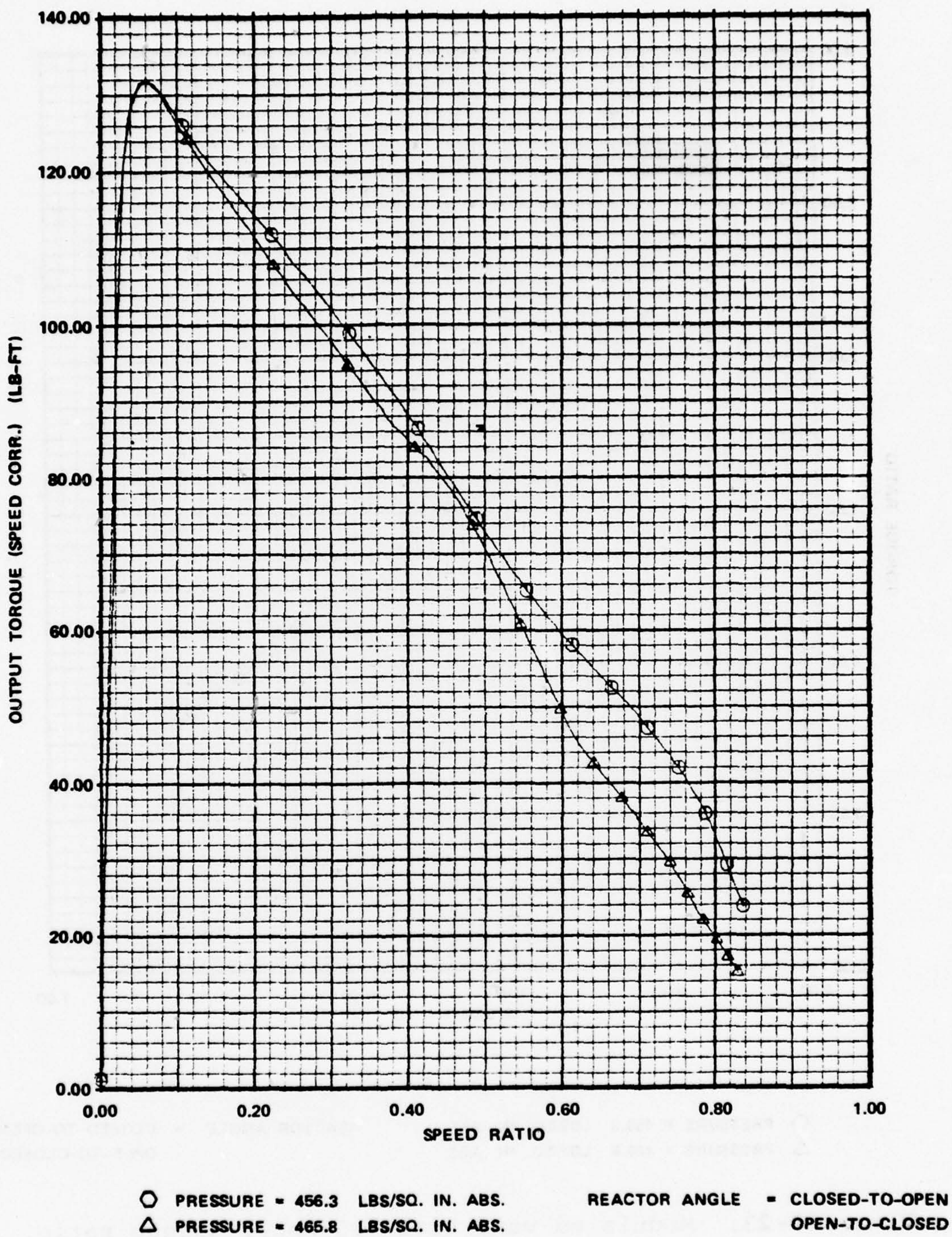


Figure A-22. Modulated vane test (15 sec), output torque.

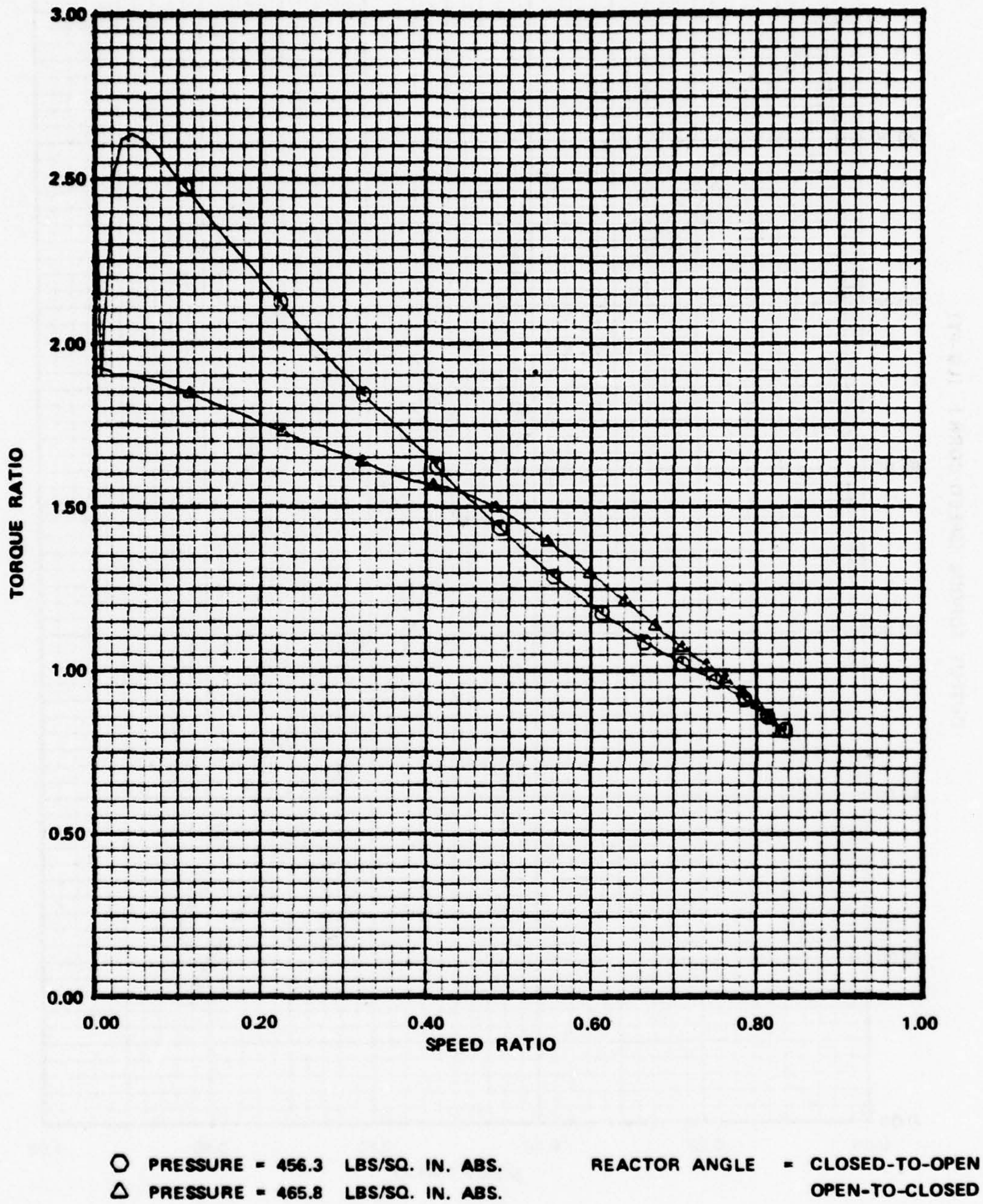
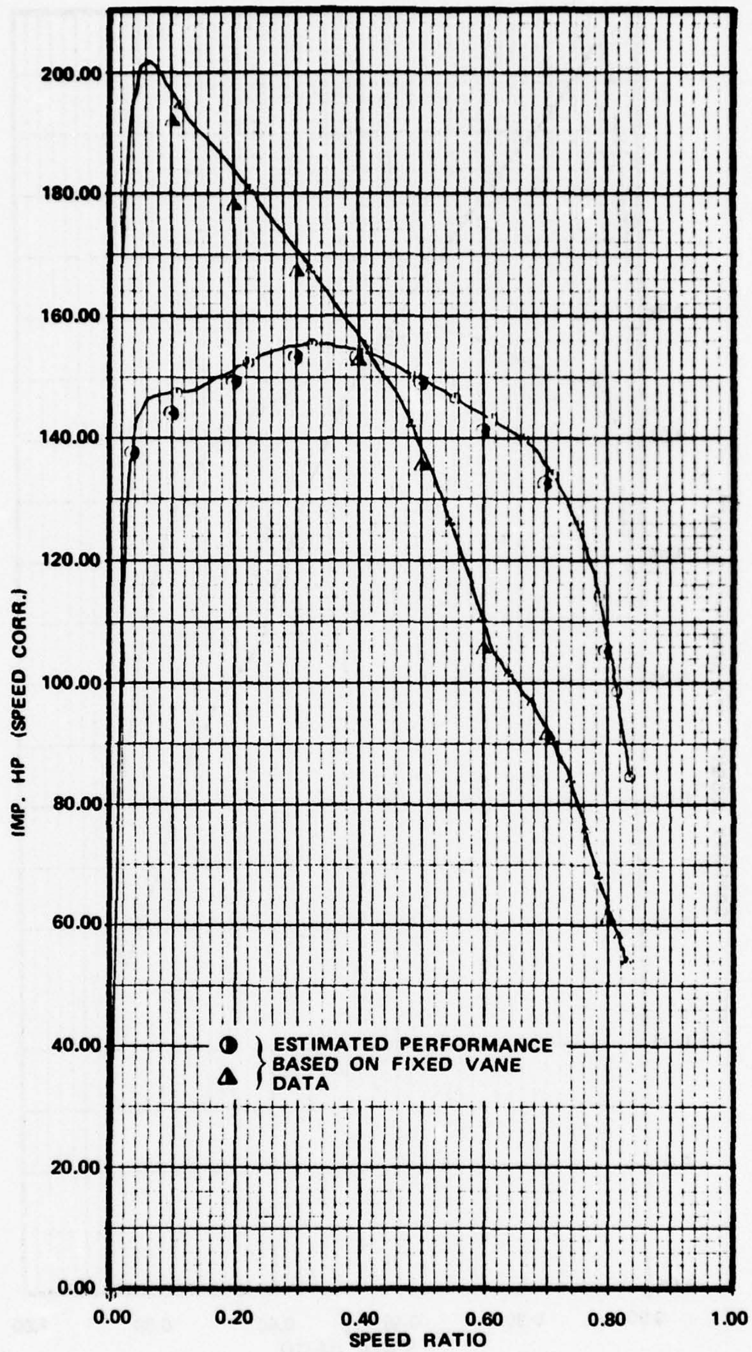


Figure A-23. Modulated vane test (15 sec), torque ratio.



○ PRESSURE = 456.3 LBS/SQ. IN. ABS. REACTOR ANGLE = CLOSED-TO-OPEN

△ PRESSURE = 465.8 LBS/SQ. IN. ABS. OPEN-TO-CLOSED

Figure A-24. Modulated vane test (15 sec), impeller hp.

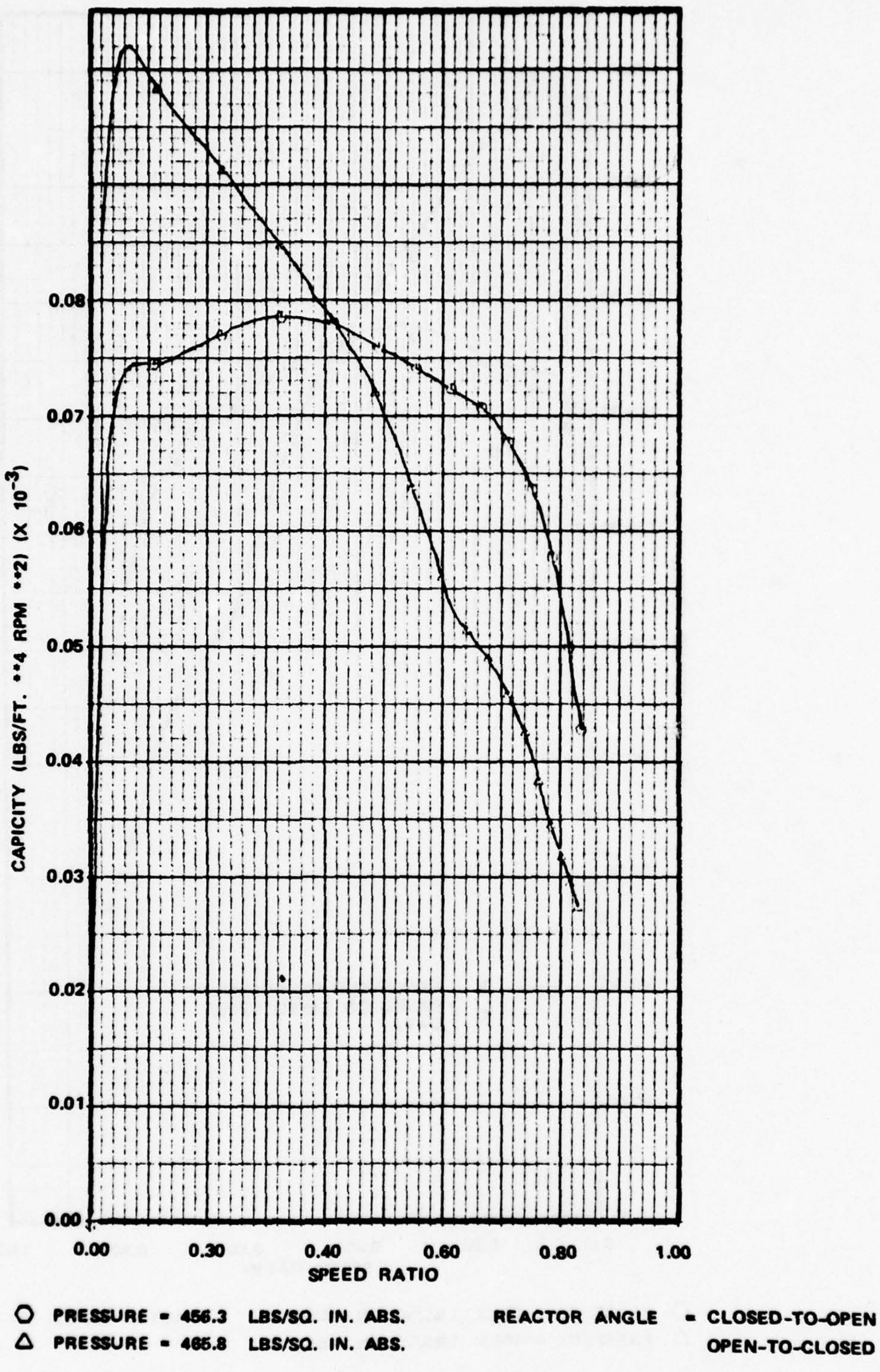


Figure A-25. Modulated vane test (15 sec), capacity.

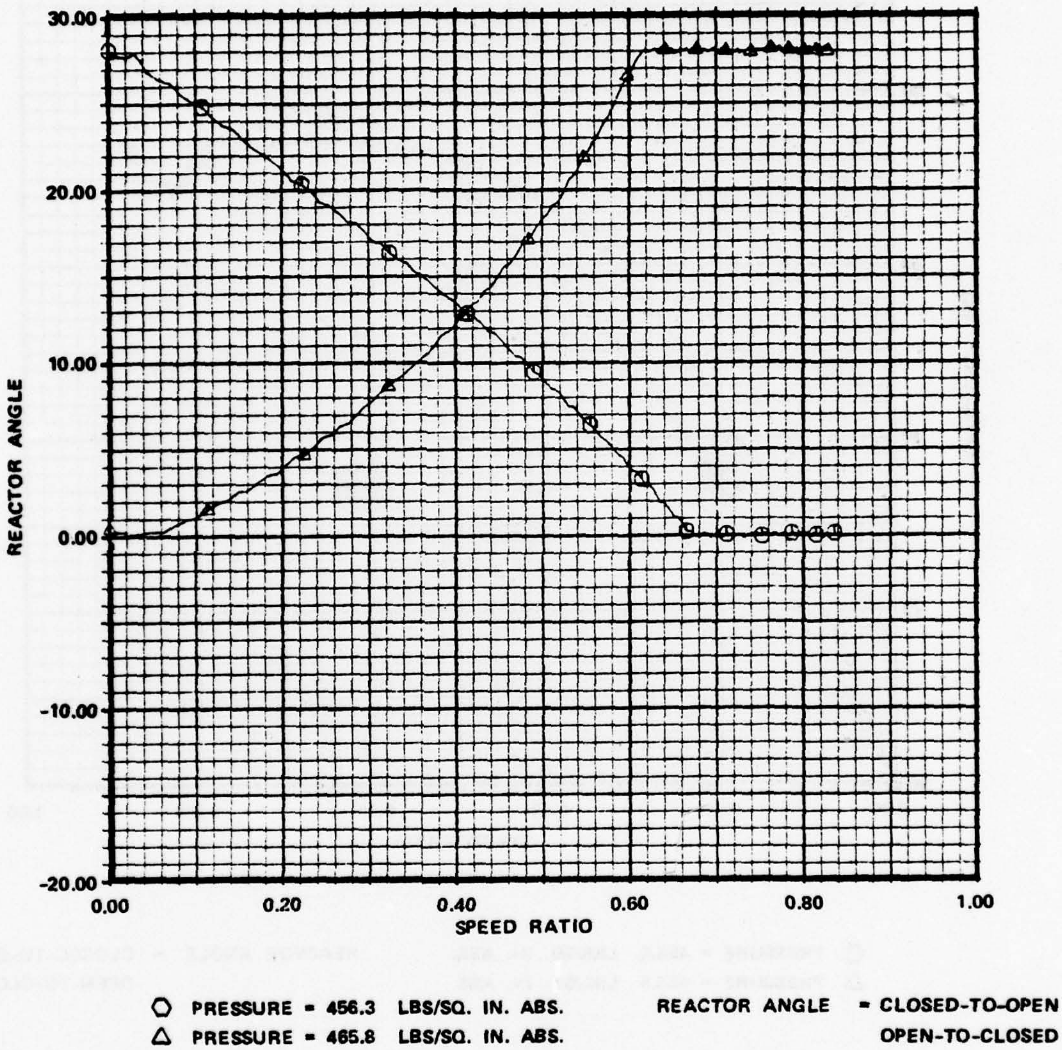


Figure A-26. Modulated vane test (15 sec), reactor angle.

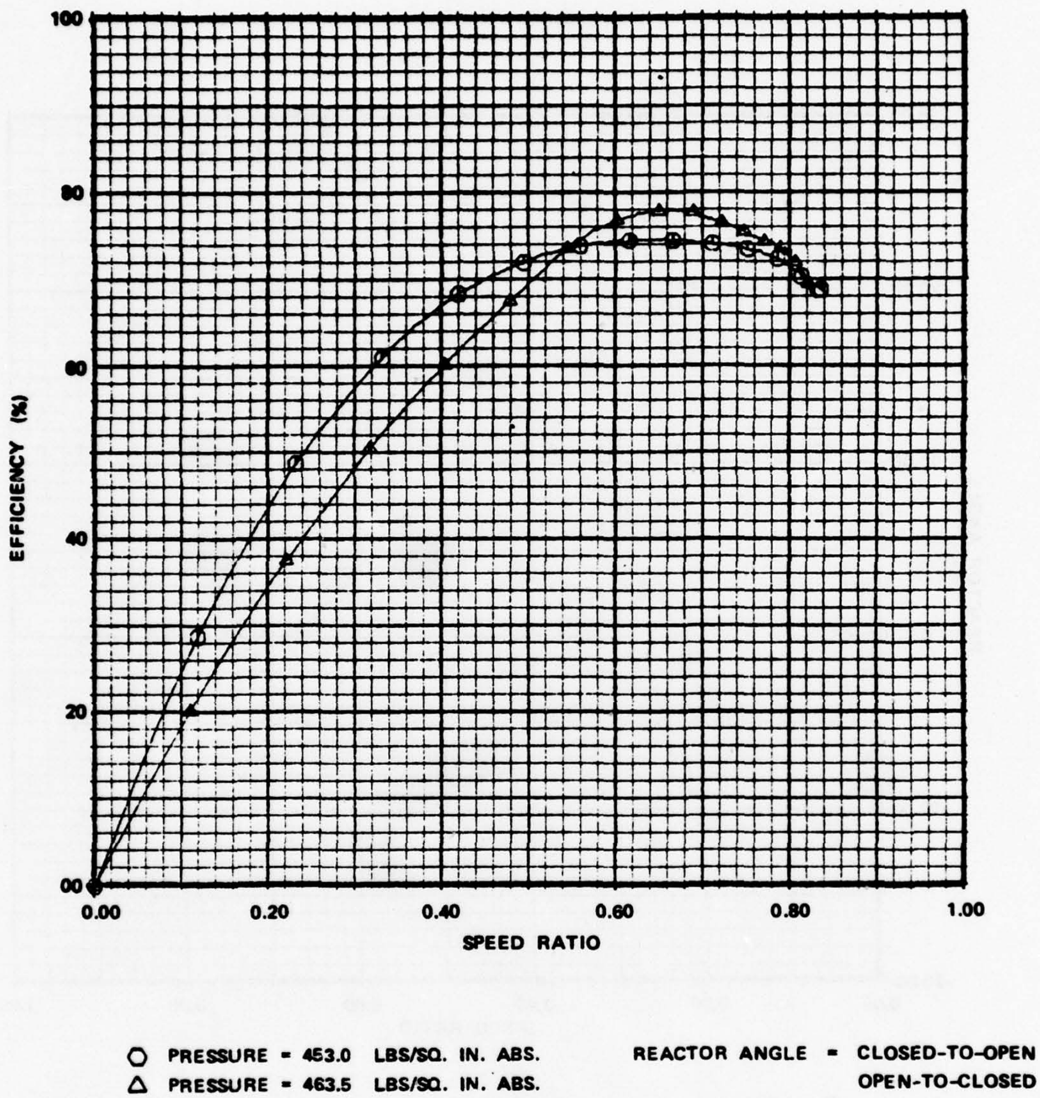


Figure A-27. Modulated vane test (20 sec), efficiency.

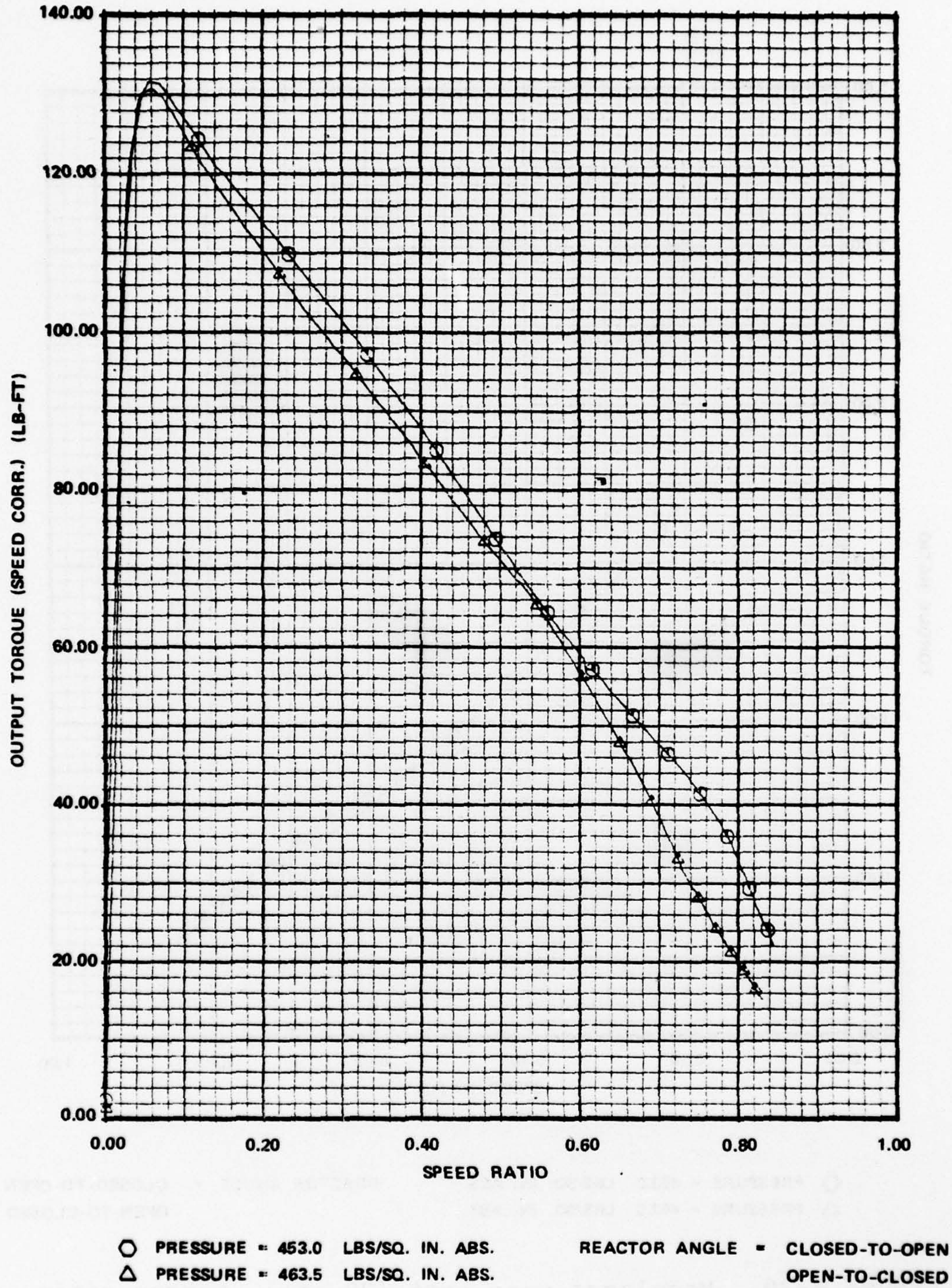
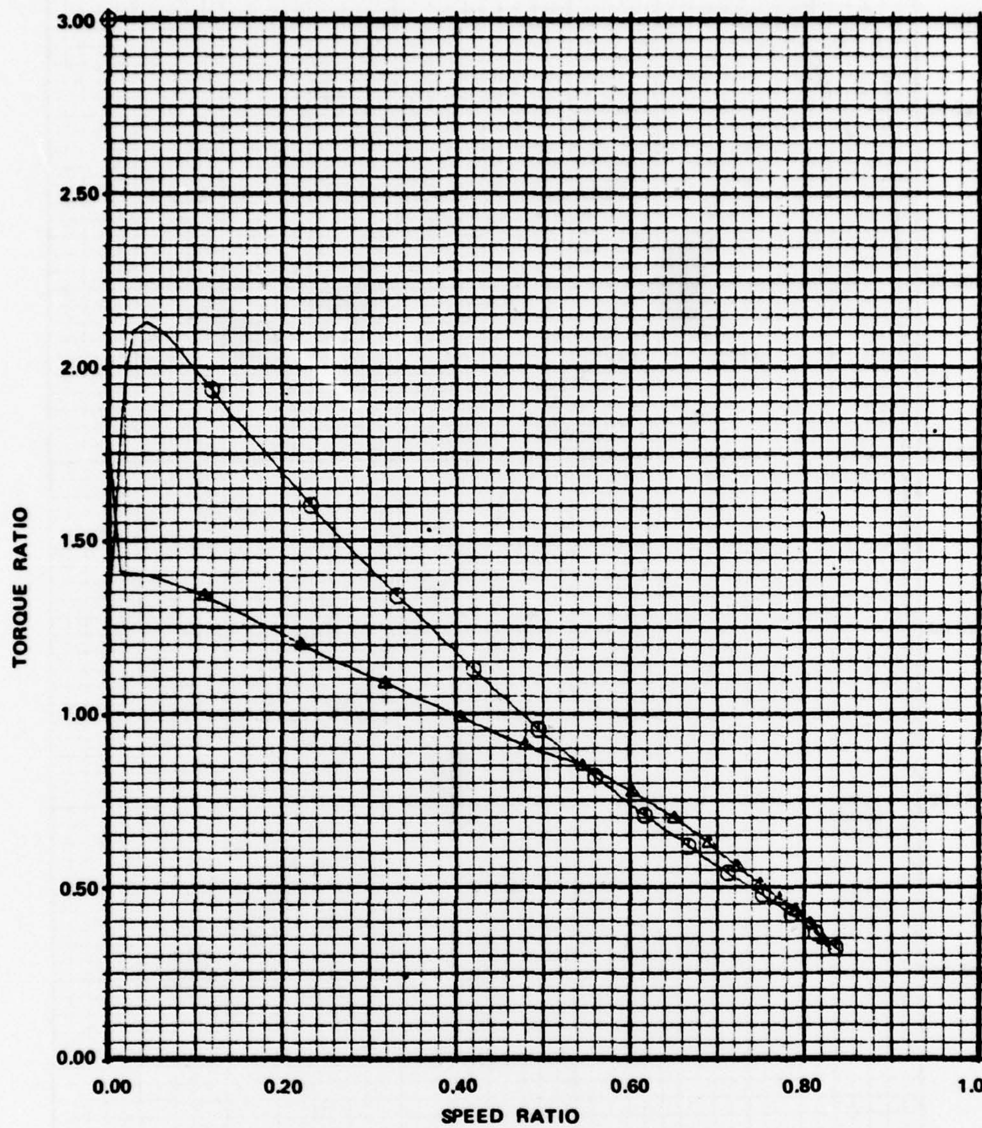


Figure A-28. Modulated vane test (20 sec), output torque.



○ PRESSURE = 453.0 LBS/SQ. IN. ABS. REACTOR ANGLE = CLOSED-TO-OPEN
△ PRESSURE = 463.5 LBS/SQ. IN. ABS. OPEN-TO-CLOSED

Figure A-29. Modulated vane test (20 sec), torque ratio.

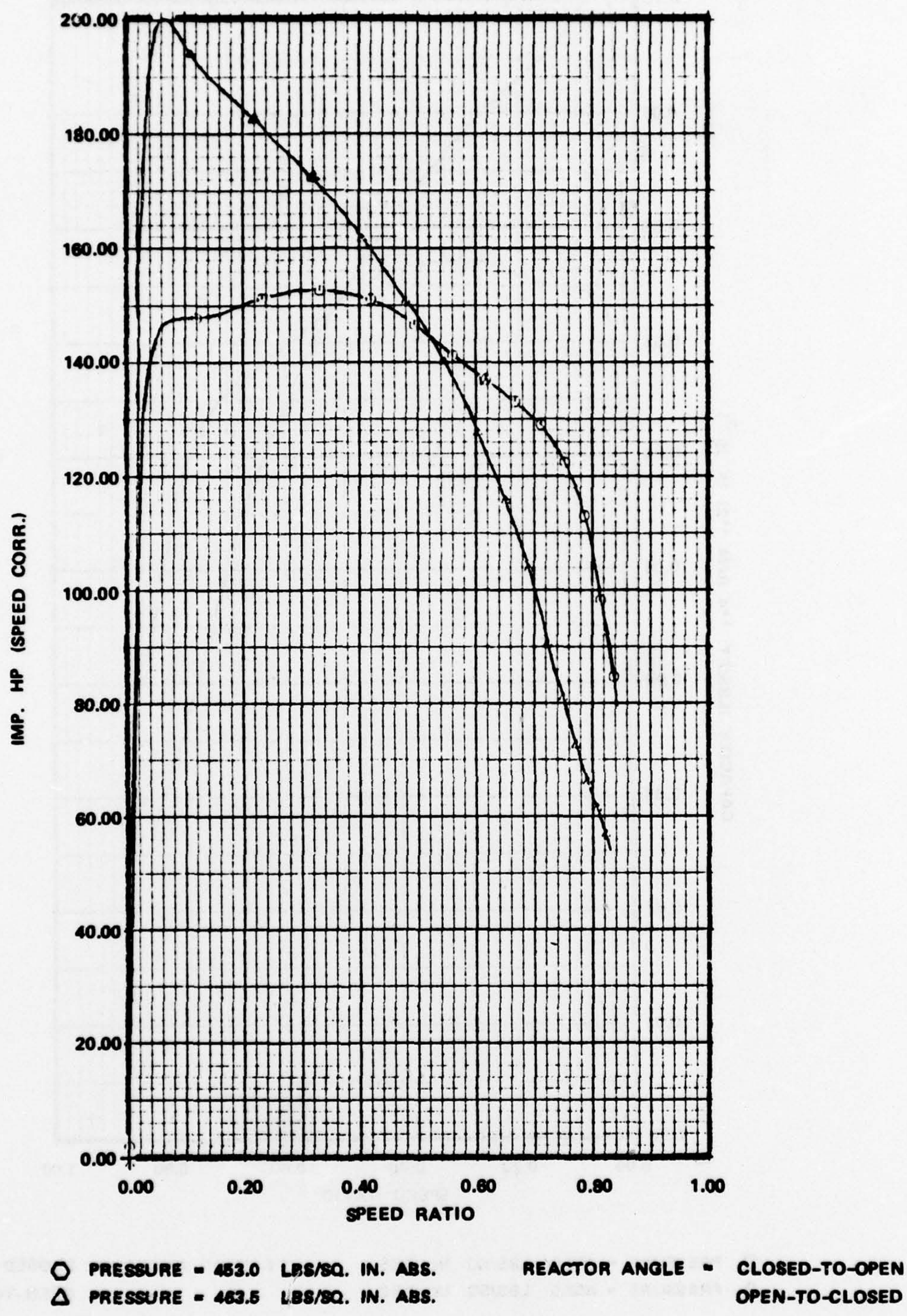
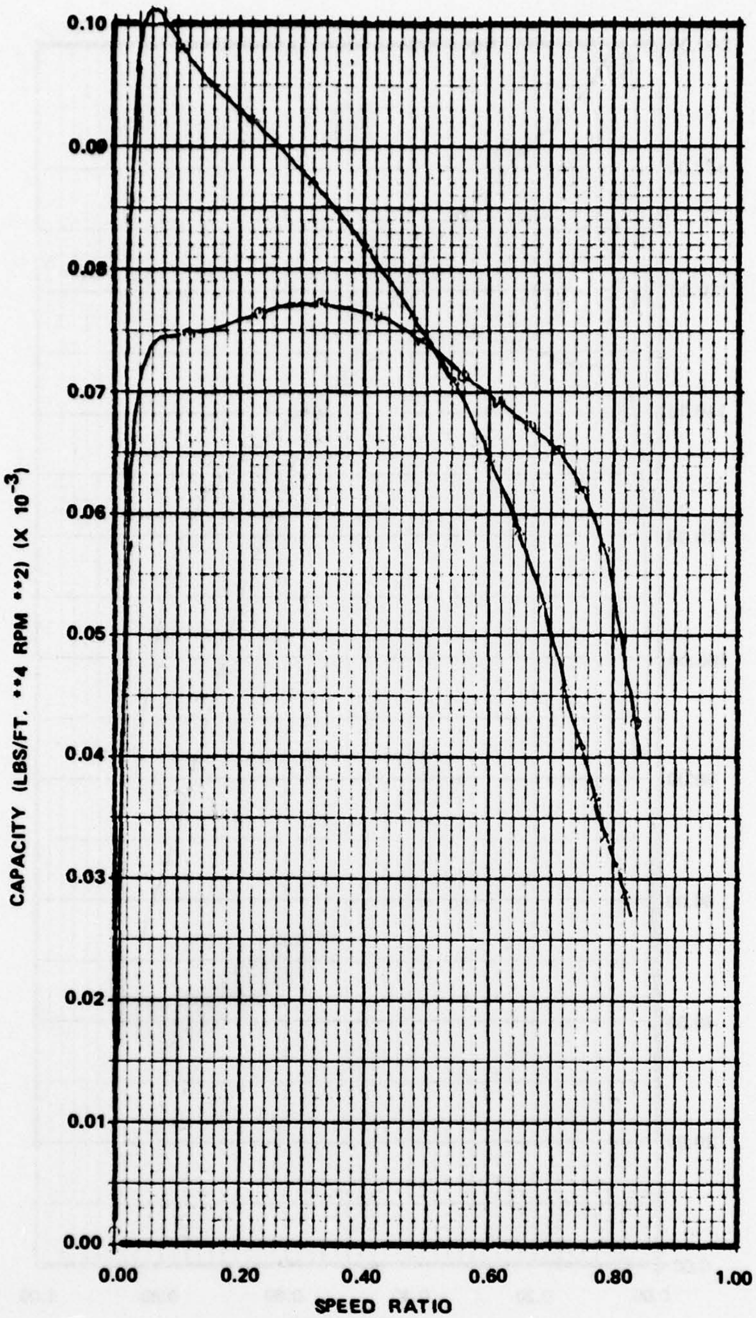


Figure A-30. Modulated vane test (20 sec), impeller hp.



○ PRESSURE = 453.0 LBS/SQ. IN. ABS. REACTOR ANGLE = CLOSED-TO-OPEN
△ PRESSURE = 463.5 LBS/SQ. IN. ABS. OPEN-TO-CLOSED

Figure A-31. Modulated vane test (20 sec), capacity.

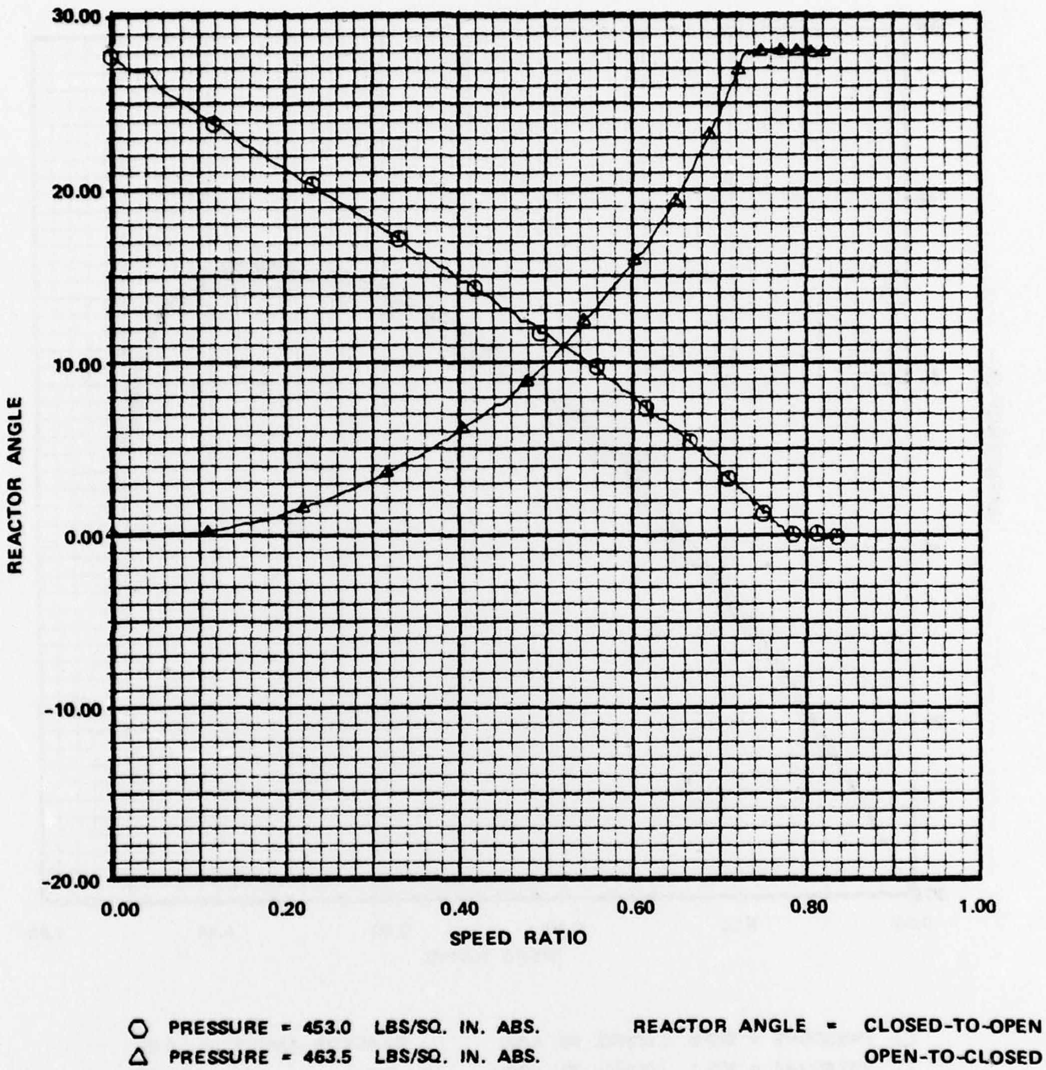


Figure A-32. Modulated vane test (20 sec), reactor angle.

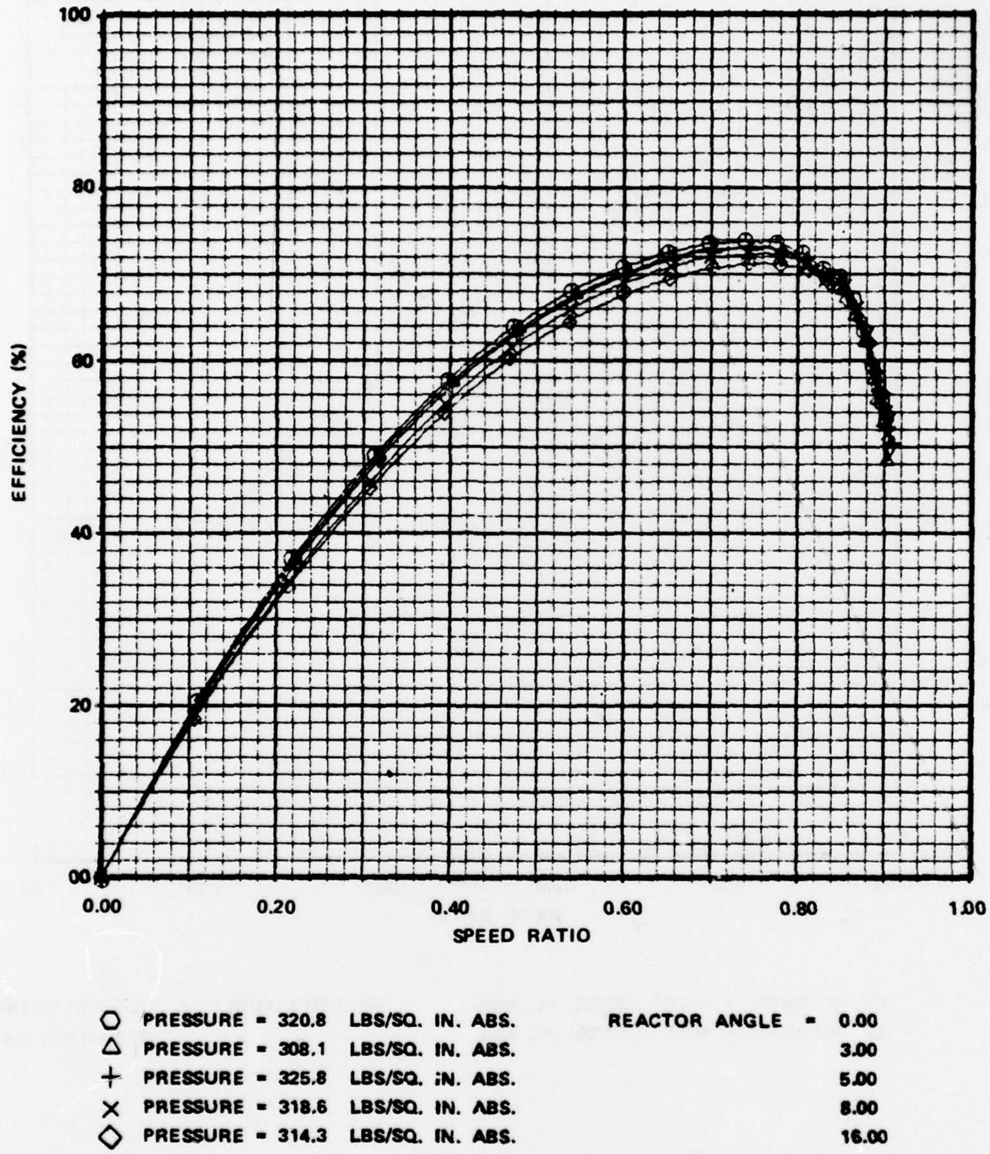


Figure A-33. Over-open fixed vane test (300 psig), efficiency.

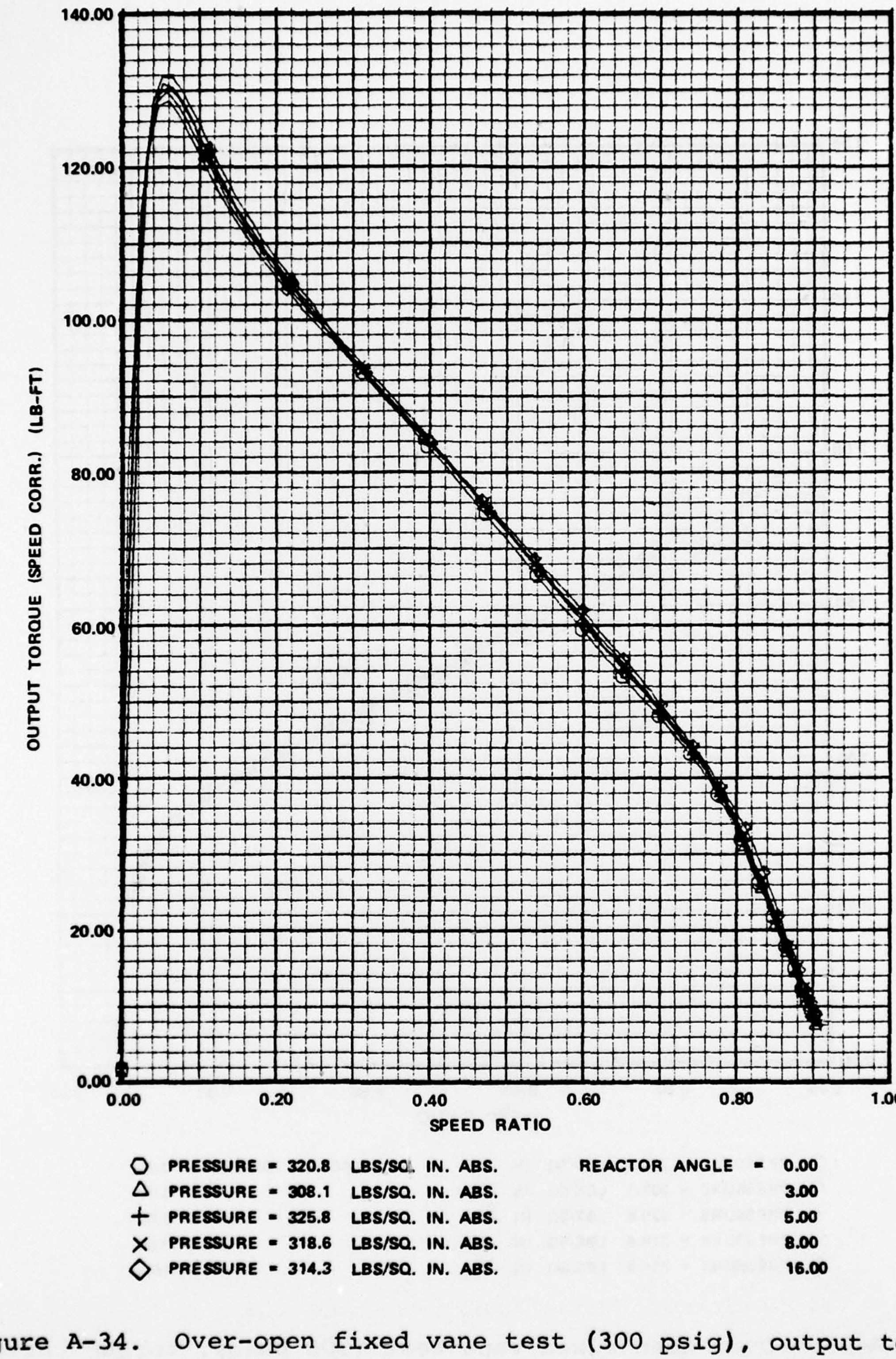
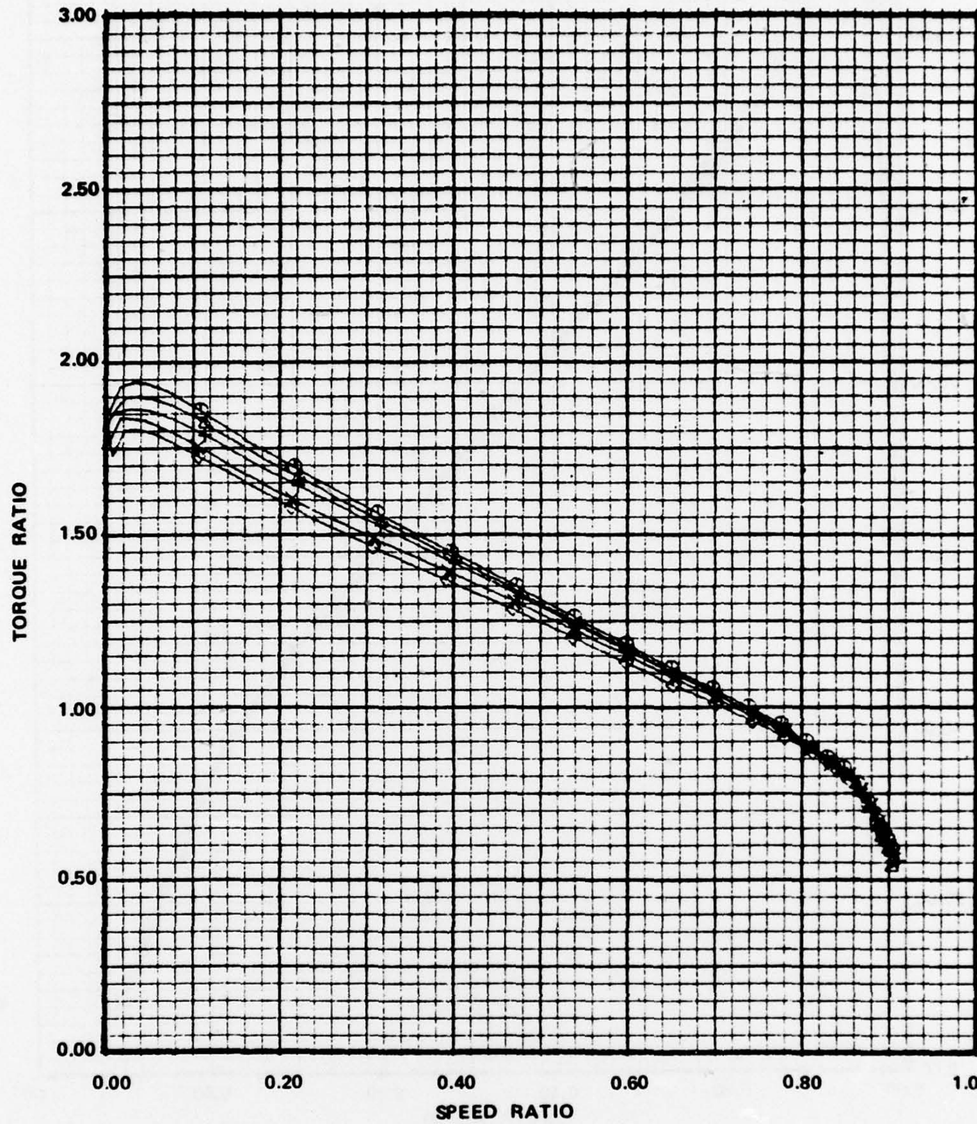
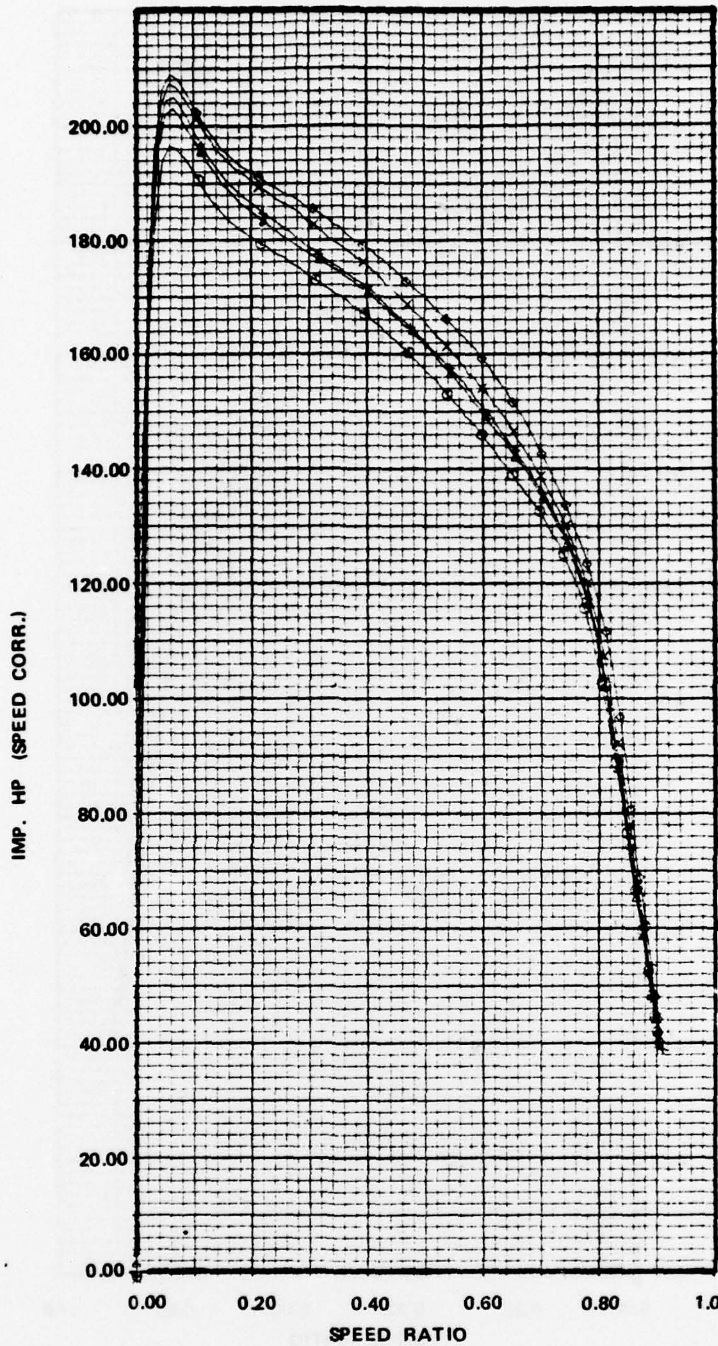


Figure A-34. Over-open fixed vane test (300 psig), output torque.



○	PRESSURE = 320.8 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.00
△	PRESSURE = 308.1 LBS/SQ. IN. ABS.		3.00
+	PRESSURE = 325.8 LBS/SQ. IN. ABS.		5.00
×	PRESSURE = 318.6 LBS/SQ. IN. ABS.		8.00
◇	PRESSURE = 314.3 LBS/SQ. IN. ABS.		16.00

Figure A-35. Over-open fixed vane test (300 psig), torque ratio.



○ PRESSURE = 320.8 LBS/SQ. IN. ABS.	REACTOR ANGLE =	0.00
△ PRESSURE = 308.1 LBS/SQ. IN. ABS.		3.00
+ PRESSURE = 325.8 LBS/SQ. IN. ABS.		5.00
× PRESSURE = 318.6 LBS/SQ. IN. ABS.		8.00
◇ PRESSURE = 314.3 LBS/SQ. IN. ABS.		16.00

Figure A-36. Over-open fixed vane test (300 psig), impeller hp.

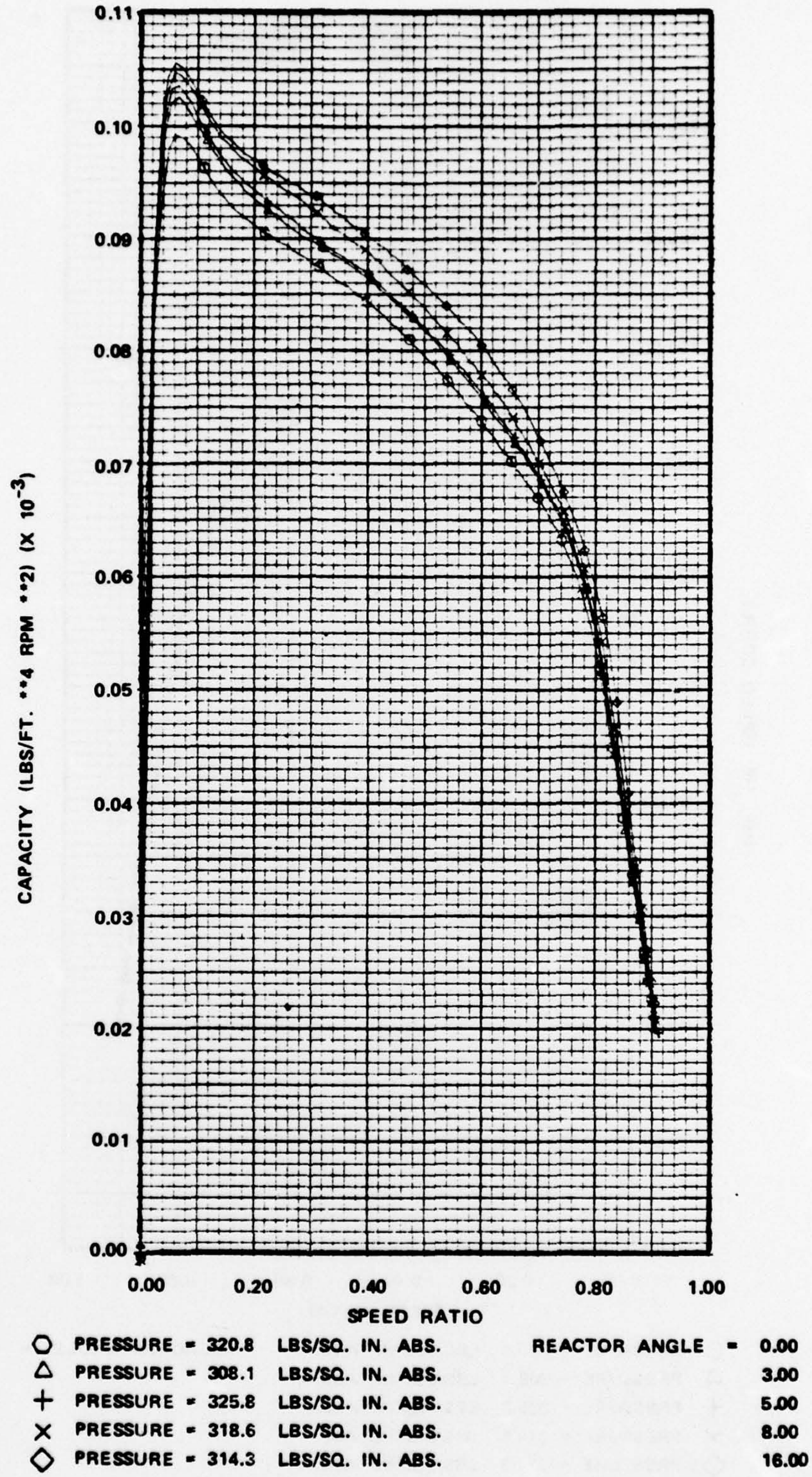


Figure A-37. Over-open fixed vane test (300 psig), capacity.

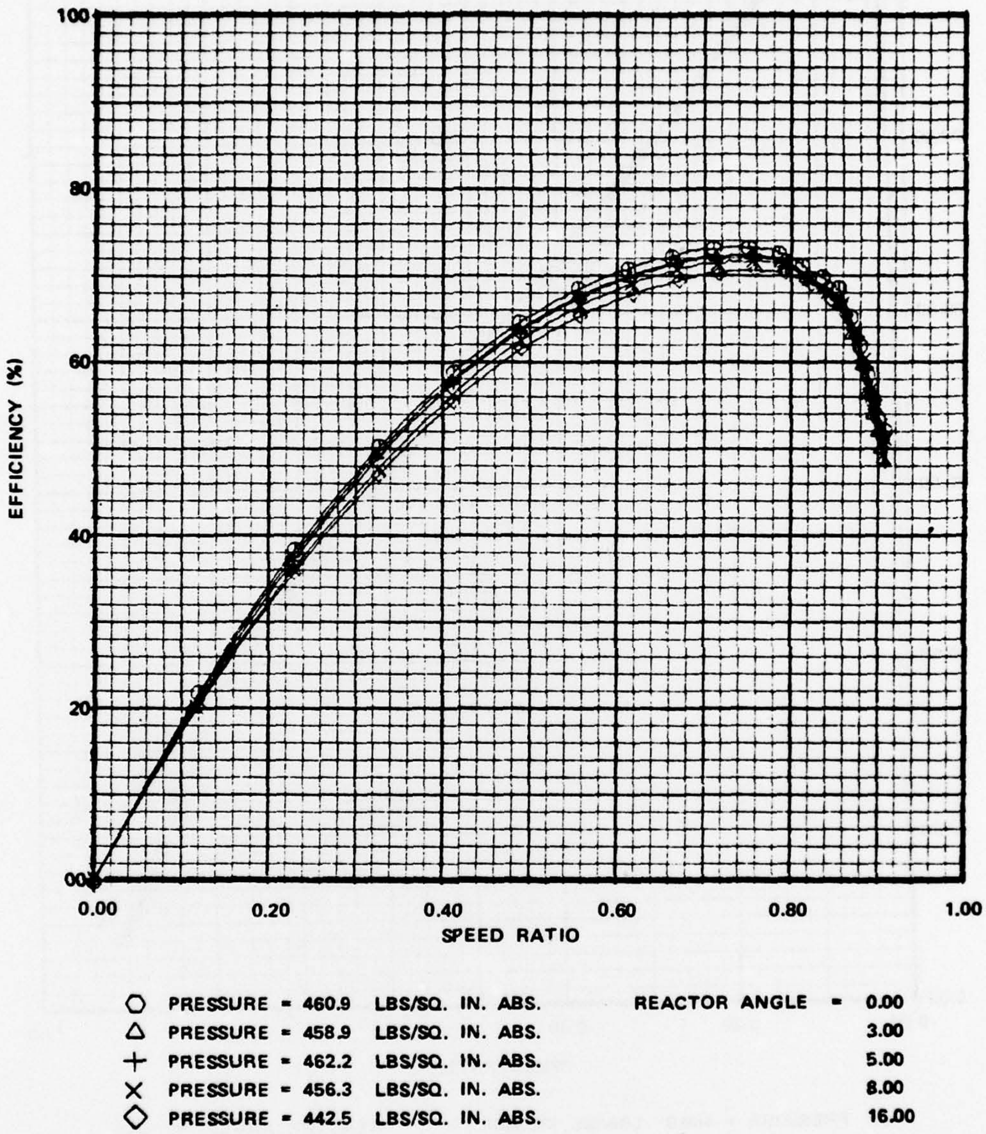


Figure A-38. Over-open fixed vane test (450 psig), efficiency.

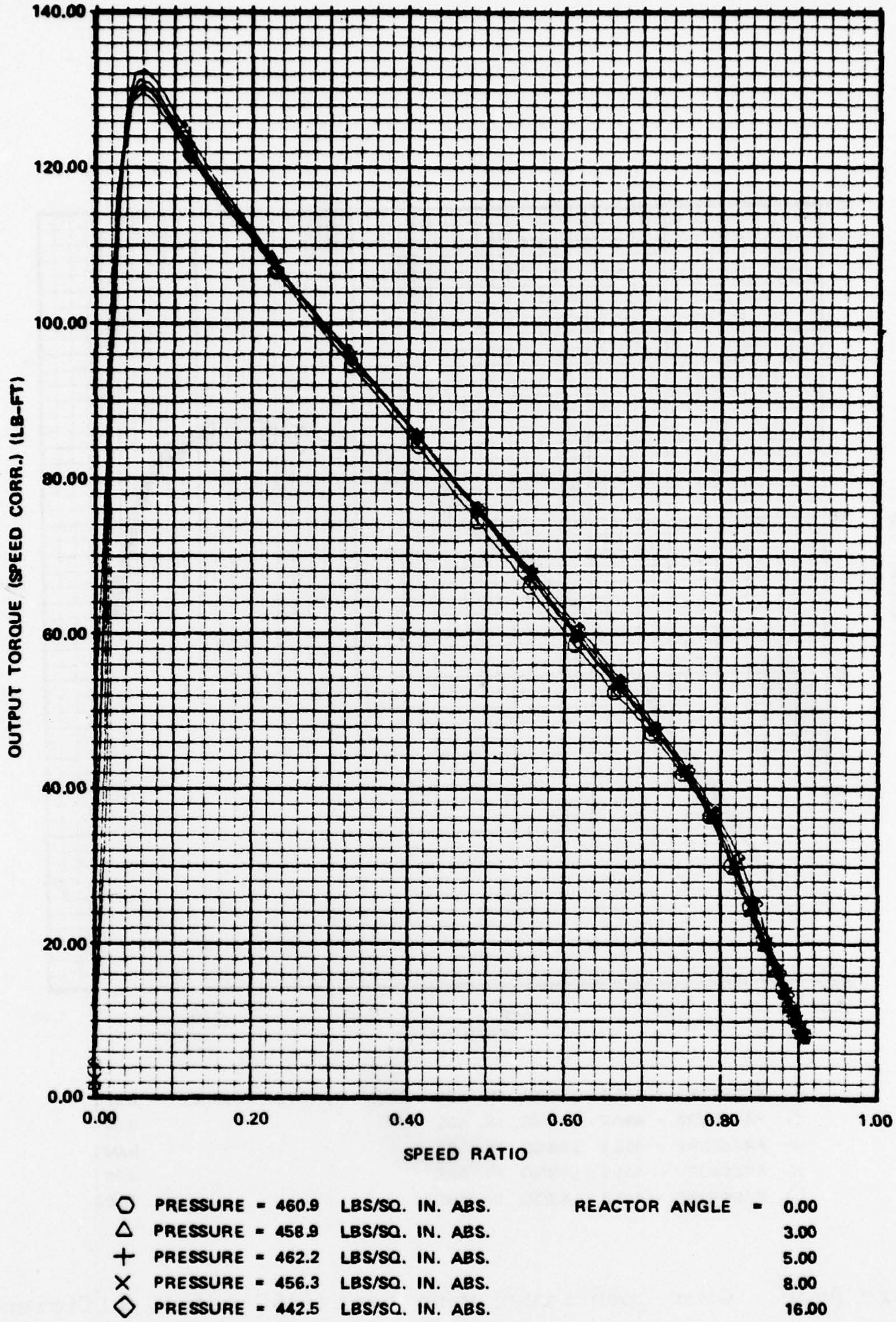


Figure A-39. Over-open fixed vane test (450 psig), output torque.

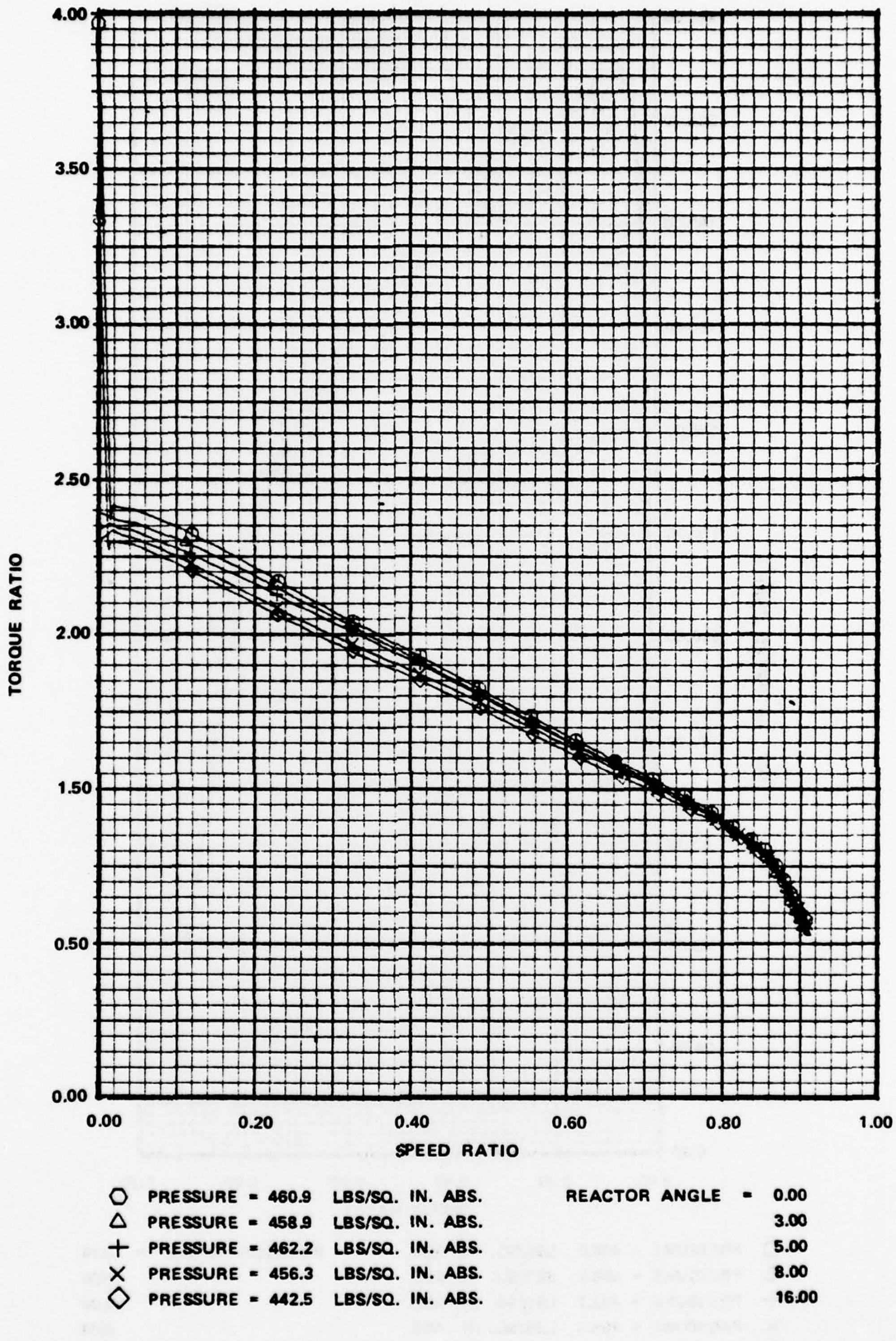


Figure A-40. Over-open fixed vane test (450 psig), torque ratio.

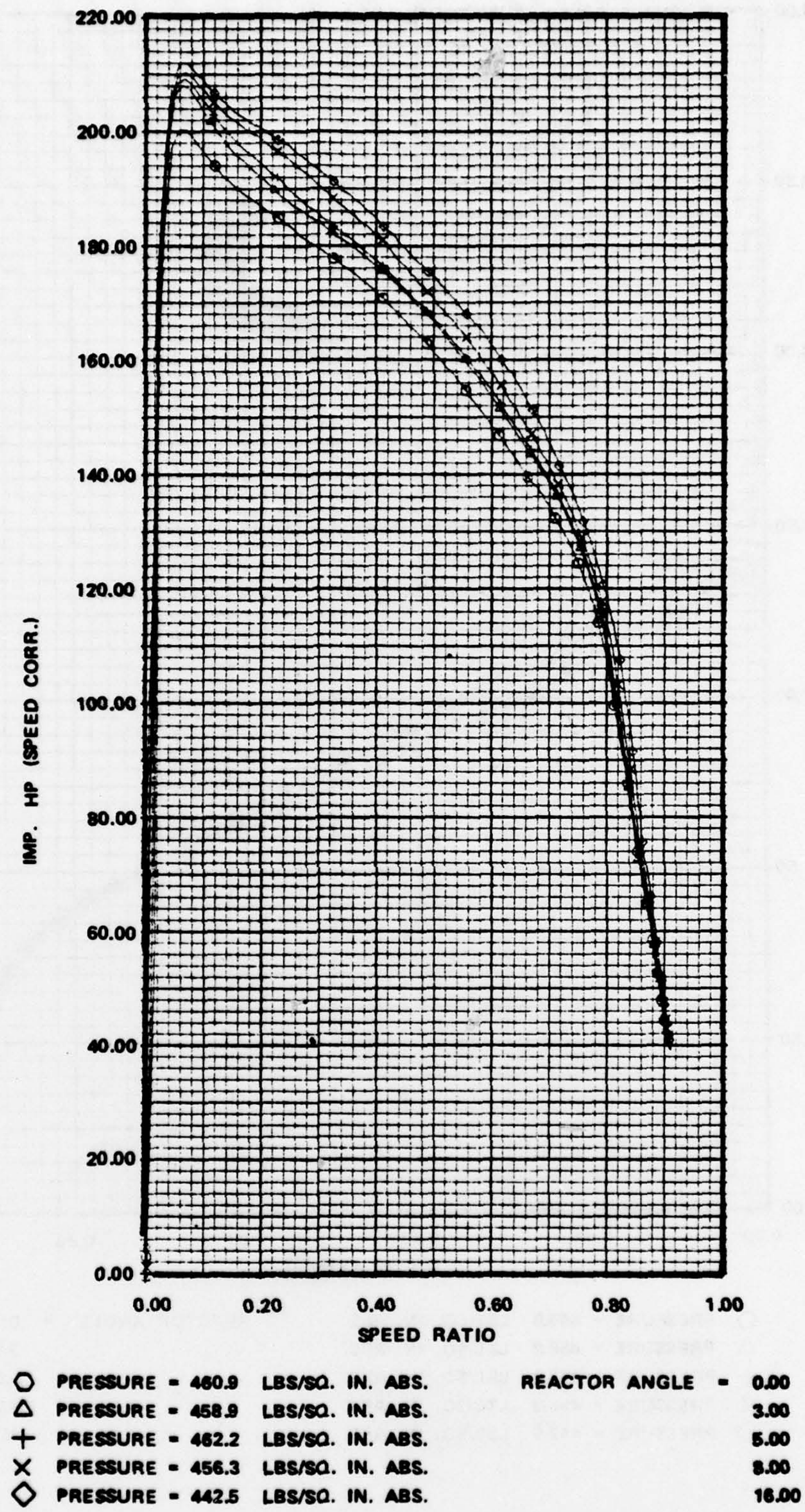


Figure A-41. Over-open fixed vane test (450 psig), impeller hp.

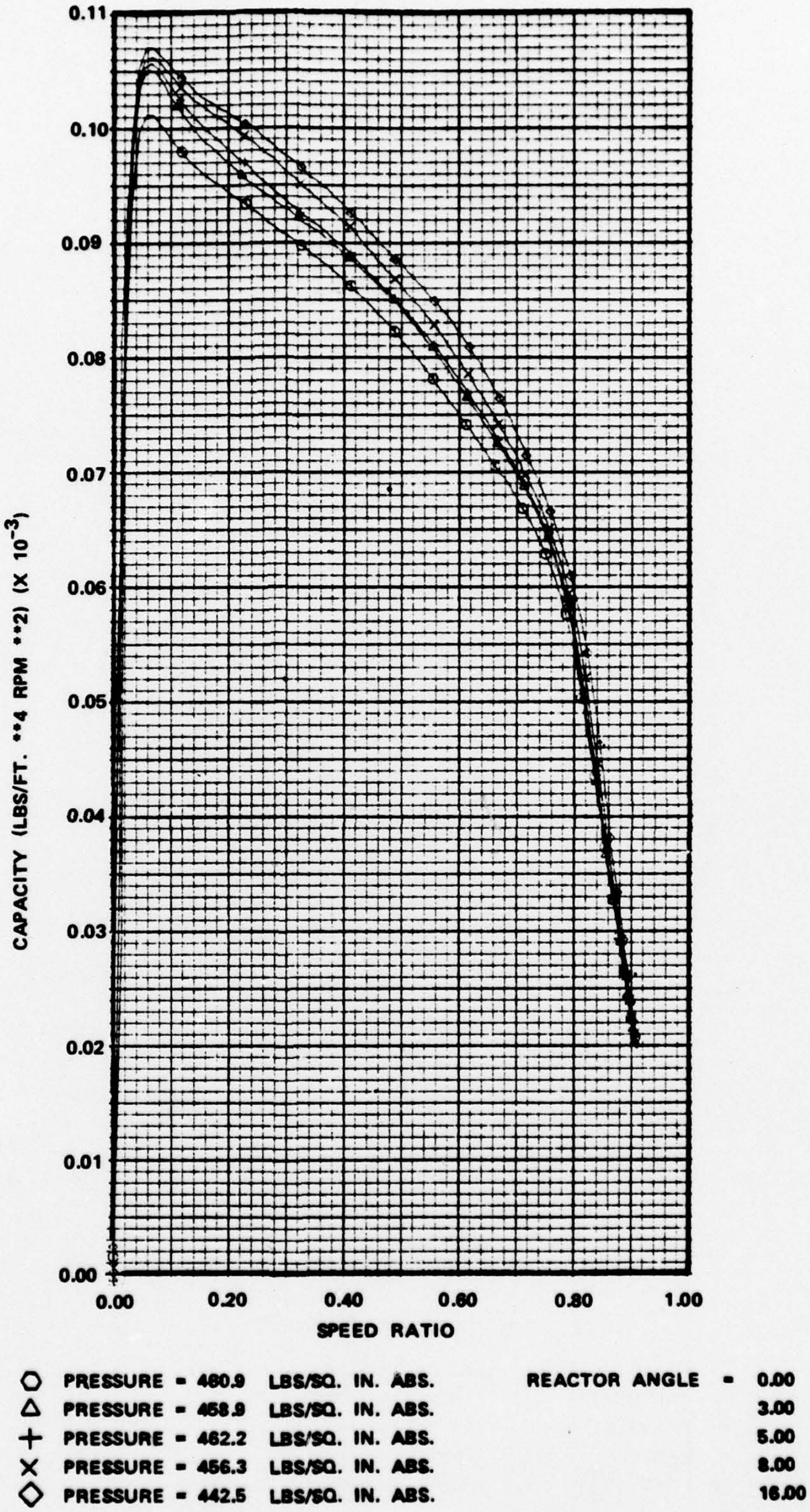


Figure A-42. Over-open fixed vane test (450 psig), capacity.

*U.S.Government Printing Office: 1978 — 757-080/703